ROPLANE DESIGN

BY F. S. BARNWELL

AND

MPLE EXPLANATION

NHERENT STABILITY

BY W. H. SAYERS

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A SIMPLE EXPLANATION *of* INHERENT STABILITY

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A FOREWORD

BY C. G. GREY, EDITOR OF "THE AEROPLANE"

SO many new firms are now entering the Aeroplane Industry, and in consequence so many trained engineers are for the first time taking a serious interest in aeronautical engineering that the time seems opportune to publish a general review of the general principles of aeroplane design.

The disquisition on the subject, which follows this preface, was originally written by Mr. F. S. Barnwell to be read as a paper before the Engineering Society of Glasgow University. It was subsequently published in serial form in "THE AEROPLANE" early in 1915, and so great and so constant was the demand for the numbers containing the treatise that it has seemed worth while to republish the whole in the form of a small book, and to append to it a short article by Mr. W. H. Sayers on the subject of The Stability of Aeroplanes, which also appeared in "THE AEROPLANE."

Mr. Barnwell's remarks on design as such will be easily understood by any constructional engineer, and his references to questions of stability will doubtless be made more understandable to those engineers who have not hitherto studied aerodynamics by Mr. Sayers' simple explanation of the why, wherefore, and how of stable aeroplanes.

A FOREWORD

It seems well to make clear why these two writers should be taken seriously by trained and experienced engineers, especially in these days when aeronautical science is in its infancy, and when much harm has been done both to the development of aeroplanes and to the good repute of genuine aeroplane designers by people who pose as "aeronautical experts" on the strength of being able to turn out strings of incomprehensible calculations resulting from empirical formulæ based on debatable figures acquired from inconclusive experiments carried out by persons of doubtful reliability on instruments of problematic accuracy.

Certain British manufacturers of sufficient independence of character have proceeded along their own lines and have produced aeroplanes which remain unbeaten, power for power, by any in the world on the score of sheer efficiency. These machines—notably Avro two-seater "tractor" biplanes, Bristol single seater biplane Scouts, Martinsyde Scouts, and Vicker's "pusher" gun-carrier biplanes—have done more than anything else to assure to the Royal Flying Corps during 1915 that ascendancy in the air over German aircraft which has been such a notable feature of the war.

Among these machines the speediest of all up to the end of 1915 was the Bristol Scout, a tiny tractor biplane designed in 1914 by Mr. F. S. Barnwell (now a Captain, R.F.C.), with the practical help of Mr. Harry Busteed, an Australian aviator, now an officer of the Royal Naval Air

Service, and at that time in the employ of the Bristol Co.

The fact that the writing was done before the war acquits Mr. Barnwell of any charge of dabbling with the pen contrary to military custom, and his consent to read the proofs of this reprint was only prompted by the instinct of self-defence.

It is to be noted that his general method of design is approved by other aeroplane designers who have been successful in producing efficient and effective aeroplanes. Consequently the new arrival in the aircraft industry may take it that he is fairly safe in following that method.

Mr. W. H. Sayers, erstwhile an electrical and mechanical engineer of ability and experience, was one of the first properly trained engineers to take an active interest in aviation. He has been intimately connected with the aircraft industry since the earliest days of aeroplanes, and has worked indefatigably both at construction and design. He made a special study of stability in aeroplanes in the days when most of the pilots of to-day had never seen an aeroplane, and when not more than a couple of dozen people in this country could fly. The theories he then evolved by rule of thumb have since been proved mathematically correct.

For a considerable period he was on the staff of "THE AEROPLANE," and his ability to put abstruse theoretical ideas into easily understandable language proved of high value to many students of aviation. At the beginning of the war he joined the Royal Naval Air Service, and, much

as his absence from the paper is regretted, there is considerable consolation in knowing that his practical knowledge of design and construction has proved useful. He has since been promoted to Lieutenant, R.N.V.R., and appointed for technical duty with R.N.A.S., so one can only hope that in the future his ability may be turned to still better account in the King's Service.

C. G. G.

PREFACE

Written November, 1915.

THE contents of this small book originated as a paper which was read to the Glasgow University Engineering Society in the winter of 1914.

They were published during January and February by my friend, Mr. C. G. Grey in his paper " THE AEROPLANE," without any alterations or amendments

Since Mr. Grey has considered it worth re publishing in book form, I have, at his request gone over the proofs and made sundry alterations and deletions, most of small moment.

The reader must bear in mind, therefore, that the figures and constants quoted remain those which seemed reasonable at the time of first writing the Paper.

One or two clerical errors have been corrected, a fair amount of unnecessary verbiage cut out, the empirical formula for Rudder Area (on page 58) altered, and the figures for Dihedral angle (on page 62) slightly amplified.

I regret that it has not been possible for me to re-write entirely the sections on Lateral and Directional Stability, for these are treated all too scantily and inaccurately even in comparison with the rest of work.

The original " Preliminary Remarks " and

"'Conclusion" are left in, practically unaltered, for the excuses and apologies contained therein are still more necessary now than when the Paper was first written.

F. S. BARNWELL.

Bristol, 9 *Nov.*, 1915.

ERROR.—In Fig. 12, p. 54, the Reaction on the Tail is shown as a *downward* force; this is, of course, a mistake, as it would be an upward one for the flight path shown. It has not been altered as this would incur making a new block, and it does not affect the explanation of the method.

PART I

PRELIMINARY REMARKS

BEFORE starting on my subject matter I wish to make some excuses and apologies which I trust the reader will accept. Aeroplane engineering is a young science about which most people know very little; whilst those of us who do think we know something about it do not know nearly as much as we should like to. So to take a small sub-division of aeroplane design and attempt to deal with it accurately and fully would probably be of less interest to the majority than to attempt a sort of precis of the whole subject.

Hence in this brief work I try to deal with a very large subject in a manner necessarily distinctly sketchy. Now it is hard, when one must be brief, to touch on all essential points, to be lucid and to be academically accurate. It takes as much time trying to work out how to express oneself sufficiently fully, accurately, and yet briefly as to plod straight on saying everything one knows, or thinks one knows, about a subject, and, unfortunately, I have not been able to give nearly as much time as I should have liked to the working out, altering and correcting of this paper. Asking your indulgence therefore for what may be obscure, for what may be incorrect, and for what may be tedious, I shall commence on my subject.

I shall start by briefly describing of what we shall consider an aeroplane to consist, limiting my description to 3 types (see Figs (1a,) (2a), and (3a)).

An aeroplane we shall consider therefore as a machine consisting of a closed-in body in which is a seat for the pilot and (in machines other than single-seaters) a seat or seats for a passenger or passengers. In this body are also the control mechanisms for the motor and for the movable surfaces of the machine. Mounted in or on this body are the tanks for fuel and lubricant. Mounted on either the fore or aft end of this body is the motor, the only type presently worth considering being the petrol internal combustion. Directly coupled to the motor is an air propeller. Attached to the body are the main lifting surfaces, or, as I shall henceforth call them, "Aerofoils." Attached to the underside of the body is the landing gear. Attached to the rear end of the body is the tail, consisting of a fixed part called the tail plane, and a movable portion (or portions) called the elevator (or elevators) ; also attached to the rear end of the body are the movable vertical rudder and (if any) a fixed vertical surface or rear fin.

This applies, of course, to the case in which the engine and propeller are fixed to the fore end of the fuselage (as in Figs. 1a and 2a). If (as in Fig. 3a) the engine and propeller are at the rear end of the fuselage, then the tail, rudder and fin must be attached to suitable outriggers, which are clear of the propeller disc.

You will note that I have described only the

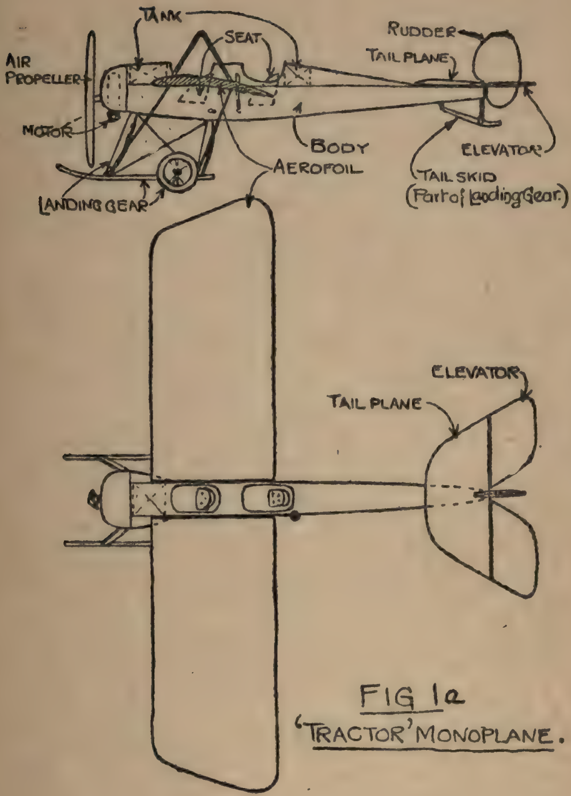


FIG 1a

'TRACTOR' MONOPLANE.

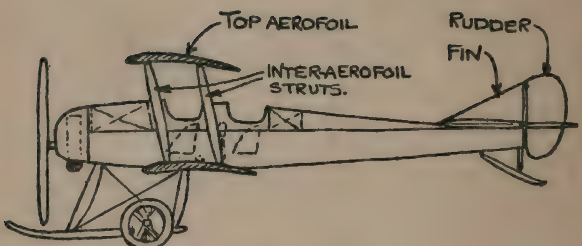


FIG. 2a.

'TRACTOR' BIPLANE.

Top Plan approximately same as for Tractor Monoplane.

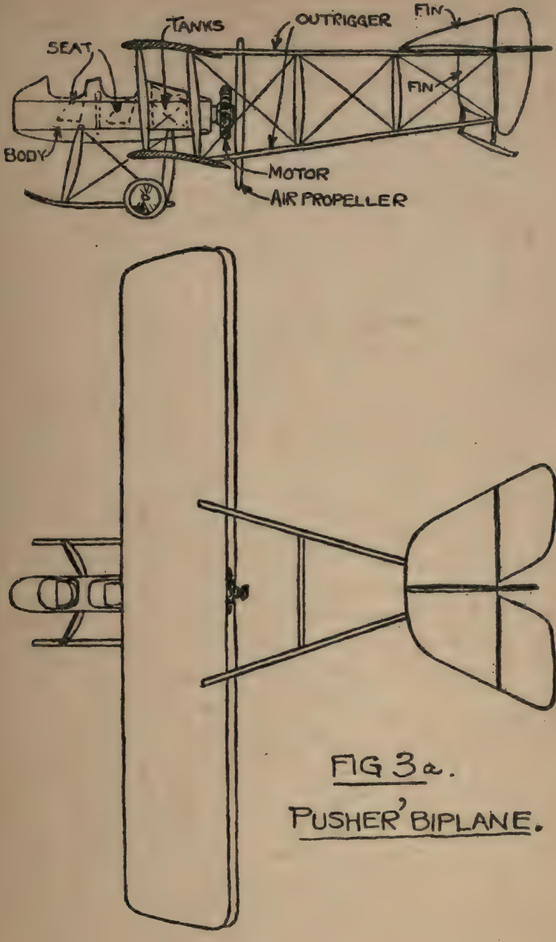


FIG 3a.

PUSHER' BIPLANE.

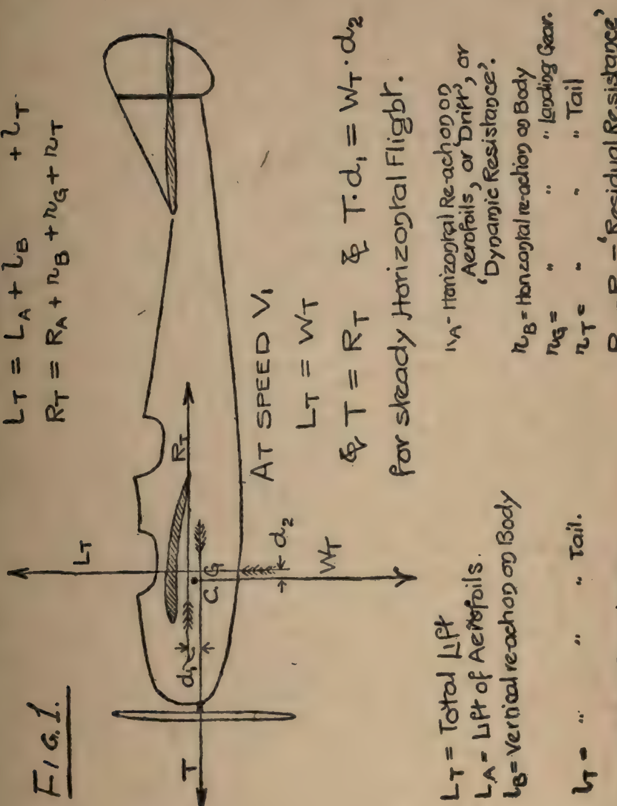
direct-driven "tractor" monoplane and biplane, and the direct-driven "pusher" biplane. I think that at present these three types contain the greatest number of desirable features, and it is not advisable in the scope of this paper to discuss further types, however tempting their points for future development may appear.

It is necessary to consider now the functioning of an aeroplane in the simplest conditions and to arrive at the primary necessities for the machine's fulfilling these conditions. Let us consider an aeroplane of total weight, W_T, travelling at some uniform velocity V_1, in a straight line and horizontally (Fig. 1).

The forces acting on this machine are (1) its weight vertically downwards, (2) total "lift" of whole machine vertically upwards (note here that I say advisedly of "whole" machine), (3) thrust of air propeller in and along direction of flight, (4) total head-resistance of whole machine in and opposite to direction of flight.

For the maintenance of this condition of straight horizontal flight it is obvious that at this speed V_1, total "lift" of machine must be equal to total weight, and propeller thrust must be equal to total head resistance. Further, if, as is most probable, the line of action of total head resistance does not coincide with that of thrust, then the C.G. (centre of gravity) of the whole machine must be such a distance in front of the line of action of total lift if thrust be below head resistance, or behind if thrust be above head resistance, that the weight-lift couple is equal to, and of opposite sign to, the

FIG. 1.


$L_T = L_A + l_B + l_T$
$R_T = R_A + r_B + r_G + r_T$
AT SPEED V_1
$L_T = W_T$
& $T = R_T$ & $T \cdot d_1 = W_T \cdot d_2$
For steady Horizontal Flight.
r_A = Horizontal Re-action on Aerofoils, or 'Drift', or 'Dynamic Resistance'.
r_B = Horizontal re-action on Body
r_G = " " " landing Gear.
r_T = " " " Tail
$R_T - R_A$ = 'Residual Resistance' R_R
L_T = Total Lift
L_A = Lift of Aerofoils.
l_B = Vertical re-action on Body
l_T = " " " Tail.
R_T = Total Resistance.
T
L_T
R_T
C.G
d_1
d_2
W_T

thrust-head-resistance couple. In an ideal design, thrust, head-resistance, and lift should all pass through the C.G. and they generally do so approximately. But if it be impossible to attain this, it is preferable that thrust should be kept as nearly as possible through the C.G., or slightly below it, and head-resistance kept above thrust; but in neither case should the divergence be great.

It is necessary now to consider these four forces in more detail. The total weight, W_T, for any particular machine is a constant—at least, we may consider it so, since in preliminary design one always considers the machine as fully loaded. The total lift, L_T, is the sum of several forces which all vary according to the attitude of the machine to its flight-path, and which also all vary approximately as the square of the speed. We shall consider it as made up of lift of aerofoils L_A, vertical reaction on body of machine l_B, and vertical reaction on tail of machine l_T. I call it "lift," for aerofoils only, for it may be a downward force on one or other, or both, of the other members.

The thrust of the air propeller, T, depends upon the power given to it, upon its efficiency E, upon its revolutions per second r, and upon the speed along the flight-path v. It is matter for discussion later.

The total head-resistance, R_T, we shall consider as the sum of the horizontal reactions upon the aerofoils (which we shall call henceforth "dynamic resistance" or "drift," and denote by R_A), upon the body r_B, upon the landing gear r_G, and

upon the tail rT. We shall henceforth call total head-resistance minus "dynamic head-resistance," "residual head-resistance," and denote it by Rr.

Having noted what kind of machine we have to design and the elementary conditions necessary for it to fly in a straight line; I had better turn next to the consideration of our sources of data, for designing the various members of the machine.

MOTORS.

The motor is the most expensive, the most important, and the heaviest single item, and it must be properly mounted, cooled and fed.

It is useful and convenient to prepare a table of motors, as shown in Fig. 2. In the first column we have name and type of motor ; in the second normal full b.h.p. ; in the third, r.p.s. of motor at this power ; in the fourth, weight of motor in lbs. complete with carburetter, magneto, piping, etc., also radiator and water (if water cooled) ; in the fifth, petrol consumption in galls. hour at full normal power ; in the sixth, the same for lubricant ; in the seventh, weight of suitable mounting and suitable shields or "cowling" ; in the eighth, weight of suitable air propeller with coupling ; in the ninth, tenth, eleventh, twelfth and thirteenth columns we have total weight of motor (complete as in col. 4) with mounting, cowling, propeller, petrol, lubricant and tanks, for 2, 4, 6, 8 and 10 hours running respectively, at full normal power.

As to how the figures in this table are obtained. Weight of motor complete is given us by the makers, likewise the power, revs., and petrol and oil consumption. The weight of a suitable mounting is a matter of deduction from the actual weights of satisfactory mountings for known cases. I have assumed that weight of mounting varies directly as weight of motor, and have taken it as 1-7th weight of motor for a rotary, and 1-10th weight of motor for a stationary engine.

① NAME & TYPE OF MOTOR	② Full Normal BHP	③ R.P.S. at Full Normal BHP.	④ Weight of Motor Complete	⑤ Petrol Cons. Galls	⑥ Oil Cons. /Hour	⑦ Wgt of Mtg. etc	⑧ Wgt of Propeller	⑨ W 2 Hours	⑩ W 4 Hours	⑪ W 6 Hours	⑫ W 8 Hours	⑬ W 10 Hours
50 HP GNOME Rotary A.C	38	20	170	5·0	1·0	50	19	349	459	569	679	789
80 HP Gnome Rotary A.C.	68	20	210	7·5	1·7	59	25	464	634	804	974	1144
100 HP Gnome Rotary A.C	95	20	320	10	2	82	29	651	871	1091	1311	1531
80 HP Le Rhone Rotary A.C	85	20	250	8·5	1·8	68	28	536	726	916	1106	1296
70 HP Renault Stationary A.C.	72	30	350	7·0	1·0	54	26	574	718	862	1006	1150
120 HP Austro-Daimler Stationary W.C	125	20	600	9·5	·6	80	34	892	1070	1248	1426	1604
90 HP Canton Unné Stationary W.C.	85	21	450	7·5	·6	66	28	688	832	976	1120	1264
200 HP Canton Unne Stationary W.C.	200	21	900	16	1·0	120	42	1362	1662	1962	2262	2562

TABLE FOR MOTOR WEIGHTS.

wgt ⑦ $= \frac{1}{7}$ ④ $+ 2\sqrt{④}$ in lbs., for Rotary

$= \frac{1}{10}$ ④ $+ \sqrt{④}$ for Stationary.

Wgt ⑧ $= 3\sqrt{BHP}$ in lbs

Wgt Tanks = $\frac{1}{5}$ wgt contents full.

Petrol = 7·2 lbs/gall.

Oil = 10 lbs/gall.

FIG. 2.

The weight of "cowling" I have taken as varying as the square root of the weight of the motor, and as equal to twice square root of weight of motor for a rotary, and one-half this weight for a stationary motor.

The weight of tanks I have taken as varying directly as the capacity, and as 1-5th of the weight of the contents (when full, of course), taking petrol as 7.2 lbs. per gallon, and lubricating oil at 10 lbs. per gallon.

The weight of propeller I have taken as varying as the square root of the horse-power and as numerically equal to three times square root horse-power in lbs.

All these weights are fair ones from such data as I have come across. You will understand that they are only approximate, but they are accurate enough for first estimate of weights, and probably err on the safe, that is, the heavy, side.

From this table, then, we can obtain the total weight of power plant for a considerable number of different powers and for any length of maximum power running between the extreme limits of present requirements.

AEROFOILS.

We must now consider what results we can get from aerofoils and how to estimate the weights of the other members of the machine before we can decide upon what motor to employ and commence the actual design.

Data for aerofoils are founded entirely upon experimental work. I do not think it is possible to calculate from first principles the re-actions upon a body, of any but the simplest forms, in an air current, though, of course, we can obtain by interpolation and analysis many further figures from experimentally determined bases. The method almost universally employed is that of suspending a model in a steady air current of known direction and velocity, and measuring the re-actions and moments upon it by means of a suitable balance.

Let us, then, consider an aerofoil moving at a uniform velocity in still air, or, what is equivalent as regards the air reactions upon it, stationary in a steady air current. (Fig. 3) Let us denote the area in square feet by A, the angle in degrees of the chord of the

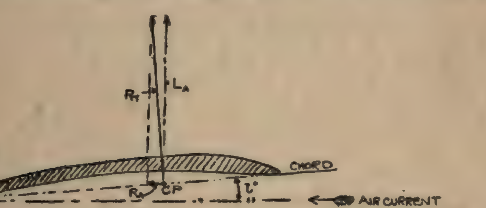


Fig. 3

Area = A □

$L_A = K_y \cdot A \cdot v^2$ } for same value for i,
$R_A = K_x\, A \cdot v^2$ } K_y & K_x are approximately constant.

wing section to the relative air current by i, and the relative air velocity in feet per sec. by v. There is, of course, a total resultant re-action RT upon this aerofoil, which it is most convenient to measure, and consider as the sum of two re-actions, one LA vertical to the direction of the air current, our "lift," the other RA along the air current, our "dynamic resistance" or "drift." For convenience in varying A and v these forces are usually tabulated for different values of i in the form of coefficients. We can write:

$$\text{Lift, } L_A = Ky\ Av^2 \text{ in lbs. weight.}$$
$$\text{Drift, } R_A = Kx\ Av^2 \text{ in lbs. weight.}$$

for these coefficients of lift and drift, Ky and Kx, are approximately constant for similar aerofoils and for the same value of i for all values of A and of v.

Our data for aerofoils, then, is based upon experimentally determined values at different values of i, for the coefficients Ky and Kx, and for the position of "centre of pressure," or intersection of line of total resultant re-action with the chord, for model size aerofoils.

It is useful to tabulate the dynamic properties of aerofoils in the following manner:—For every model for which we can get reliable data we should make on tracing cloth a standard sheet. (Fig. 4.) On each of these sheets, and in the same position, we draw an accurate scale section of its aerofoil with a standard chord length of, say, 10″. On each sheet, and in the same position, we also draw a standard squared table for its respective curves of Ky, Kx and of locus of centre of pressure, with a

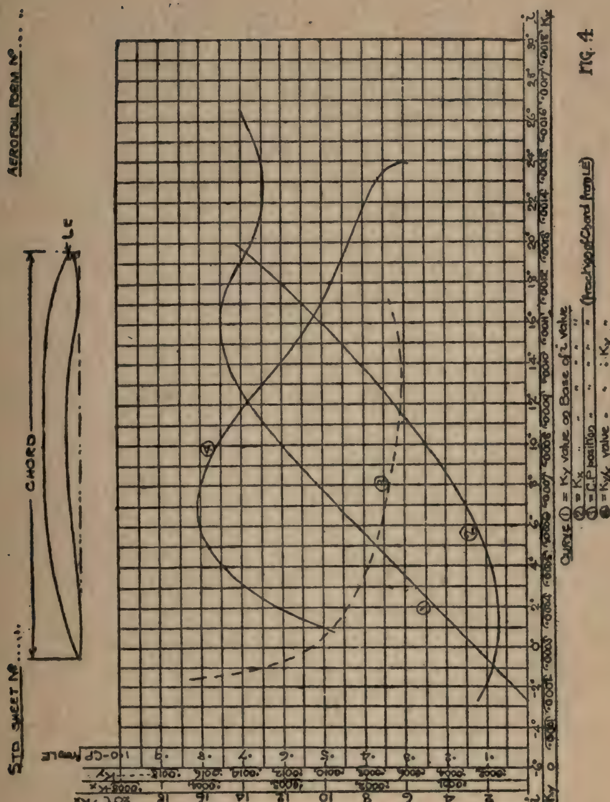

AEROFOIL FORM No. ...
STD SHEET No. ...
CHORD
LE
CURVE ① = Ky value on Base of i value
② = Kx " " " " "
③ = C.P position " " " " " (fract of Chord from LE)
④ = Ky/Kx value " " " i Ky "

FIG. 4

base of value for i (say, $\frac{1}{2}''$ representing 1° of i), and with ordinate values for both Ky and Kx (say, $\frac{1}{2}''$ representing .0001 of Ky value, and $2''$ representing .0001 of Kx value). The abscissæ values should range from -6° to $+30^\circ$ for i, and the ordinate values from 0 to .002 of Ky value. That is to say, our standard table will be $18''$ long and $10''$ high.

On this table $1''$ of ordinate value will represent a distance of centre of pressure from leading edge of aerofoil of ·1 of chord.

On this same table we draw a fourth curve of $\frac{\text{Ky}}{\text{Kx}}\left[\text{i.e., } \frac{\text{Lift}}{\text{Drift}}\right]$ value on a base of Ky value; $\frac{1}{2}''$ of ordinate value representing unity for $\frac{\text{Lift}}{\text{Drift}}$ value, and $1''$ of abscissa value representing .0001 of Ky value.

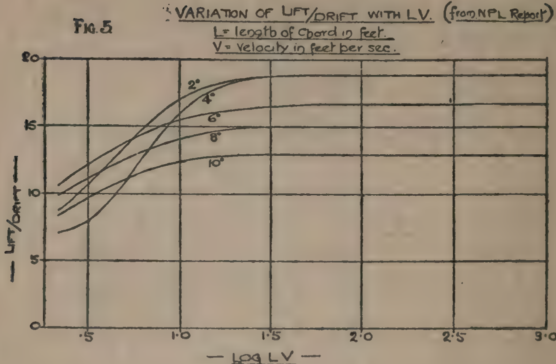
We can now, by superimposing the sheets, compare any of our aerofoil forms. The sections and tables will lie one over the other, and we can see which form gives us the best Ky (or Lift Coefficient) value at any value of i, the lowest Kx (or Drift Coefficient) value at any value of i, the least travel of centre of pressure, and the highest value for $\frac{\text{Lift}}{\text{Drift}}$ for any value of lift coefficient.

We must note here that these tables should all be for models of the same plan form, i.e., of the same ratio of Span over Chord (or "Aspect Ratio") and of the same form of ends. The National Physical Laboratory generally employs a standard

rectangular plan form of 18″ span and 3″ chord, i.e., of Aspect Ratio 6. The coefficient values should also (for absolutely safe comparison) be for the same size of model at the same air speed.

I remarked before that these coefficients were constants (for the same value of i) for varying values of both A and V. I must now, in somewhat Hibernian vein, remark that these "constants" are not quite constant. The Ky, or lift coefficient, has been found by experiment to be fairly constant for widely varying values of A and V. We shall consider it as such, and directly use model Ky values for our calculations for full-sized machines, noting that any error will probably be to the good. But the Kx, or drift coefficient, decreases slightly as A increases, and also decreases considerably as V increases. This has the meaning that the drift coefficient of our full-size aerofoil will be less than that of the model, but it also means that we cannot determine quite so accurately as we should like to, what it will be for our full-size aerofoil, especially if it be for a fast machine.

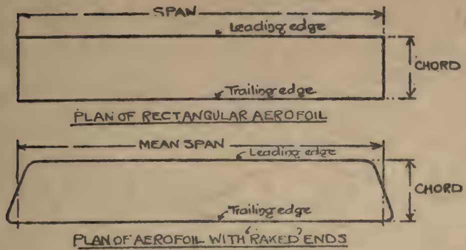
It is most probable that this difference is due to that part of the total re-action caused by skin-friction, the component of which is small in the direction of lift but large in the direction of drift; and skin-friction coefficient we know to increase both with increase of A and with increase of V^2. The best thing that we can do is to use the results which the N.P.L. gives us in the latest report of the Advisory Committee. (See Fig. 5.)



(Fig. 5.) Here we have, for several different i values, curves of lift/drift on a base of log LV, where L = length of chord in feet, and V = velocity in feet per second. By using this we can from model figures obtain fairly accurately those for a full size aerofoil at any speed.

It is necessary now to consider the effect of plan form. (Fig. 6.) Assuming first that the plan form of our aerofoils is rectangular and that we vary the Aspect Ratio only :

The National Physical Laboratory gives us this table of Lift Coefficient values, and Lift to Drift values for an aerofoil of constant section and of Aspect Ratio varying from 3 to 1 to 8 to 1 at values of i from—2° to + 20°. I suggest using this table comparatively ; i.e., suppose we have figures for a



ASPECT RATIO = $\frac{\text{SPAN}}{\text{CHORD}}$

FIG. 6.

TABLE FOR VARIATION OF ASPECT RATIO. (N.P.L.)

Value of i°	ASPECT RATIO											
	8/1		7/1		6/1		5/1		4/1		3/1	
	Ky	L/D	Ky	L/D	Ky	L/D	Ky	L/D	Ky	L/D	Ky	L/D
−2	·028	1·0	·012	·4	·044	1·8	·052	2·4	·055	2·4	·055	2·3
0	·128	6·1	·117	5·2	·109	5·2	·110	5·5	·141	6·7	·112	5·0
2	·222	11·1	·219	11·2	·212	10·7	·199	10·2	·214	9·5	·173	7·7
4	·298	14·2	·300	14·6	·289	13·8	·283	12·6	·289	11·4	·246	9·6
6	·398	15·5	·366	14·9	·372	13·4	·354	12·5	·345	11·1	·320	10·1
8	·487	14·6	·447	13·5	·469	12·7	·430	11·4	·423	10·4	·389	9·3
10	·560	13·3	·516	12·7	·536	11·5	·519	10·5	·485	9·6	·445	9·0
12	·636	12·2	·598	11·6	·612	10·7	·595	10·1	·546	8·6	·516	7·9
14	·686	10·9	·670	10·3	·686	9·9	·656	9·2	·609	8·3	·566	8·1
16	·685	8·2	·680	8·5	·686	8·3	·685	8·2	·673	7·1	·619	6·4
18	·673	5·6	·689	5·4	·686	5·7	·663	5·8	·683	5·8	·665	5·8
20	·653	3·9	·660	4·0	·662	3·9	·645	3·8	·643	3·7	·667	4·4

Ky values in above Table are in 'Absolute' units: to convert to lb., foot, sec., units multiply above values by ·00236

model of 6 to 1 Aspect Ratio and wish to calculate its properties for some other Aspect Ratio, say, 4 to 1. We shall take it that its values at 4 to 1 will be to its relative values at 6 to 1 as are the corresponding values in this table for 6 to 1 to those for 4 to 1.

It appears, from such few experiments as have been made, that it slightly increases an aerofoil's efficiency to rake the ends somewhat, making the trailing edge longer than the leading edge. This is because such a formation of ends decreases the end losses. And probably the lower the Aspect Ratio the more should the ends rake. In practice, however, it is better not to rake the ends too much, as we cannot then get the best distribution of stay attachments along both front and rear spars.

I suggest about 30° Rake for 4 to 1 Aspect Ratio, 25° for 5 to 1, and 20° for 6 to 1, but these are quite arbitrary values.

From a strength point of view it is advantageous to taper the aerofoils from root to tip. But as this means a structure considerably more difficult and costly to make, I do not think it is quite justified.

As regards choice of Aspect Ratio :—For the same surface, the lower the Aspect Ratio the stronger is the aerofoil, or the lighter for the same strength, but the lower will be the maximum Lift to Drift value and the maximum value for Lift. The efficiency at very small and very large values for i is not much effected, and, in fact, appears from this table to be rather better for the lower Aspect Ratios. We must bear in mind that a low Aspect Ratio is worse for both lateral and directional stability than a high one. Taking everything into consideration, I would suggest 5 to 1 Aspect Ratio for monoplanes and small biplanes, and 6 to 1 to 7 to 1 for large biplanes.

FIG. 7.

FIGS FOR GAP

C'_B	Ratio $\frac{GAP}{CHORD}$	C_B
·81	·4	·62
·82	·8	·77
·84	1·0	·82
·85	1·2	·86
·89	1·6	·89

C_B is multiplying factor to obtain Biplane Lift Coeff[ts] from Monoplane figures. C'_B is ditto for values for L/D.

FIGS FOR STAGGER

For stagger = ·44 Gap both Lift Coefficient & Lift/Drift value improved by about 5%

Next, for biplanes only of course, to consider the effect of gap and stagger. Fig. 7. From model experiments, we find that the greater the gap the higher the efficiency, whilst stagger also increases the efficiency somewhat. The gap amount, however, introduces the question of weight and head resistance of struts and stays, the greater the gap the greater these become. So we must compromise, and I should suggest a gap of .8 of Chord up to equal to Chord, the smaller value for fast and relatively high-powered machines, the larger for slower and less highly powered ones.

The increase in efficiency is not very great in a staggered disposition, and it increases structural difficulties, especially if the means for obtaining lateral control is by warping the aerofoils. Stagger may, however, be of considerable value for improving the view obtainable downwards from the machine. Hence, I should suggest that the question of stagger should mainly depend upon the disposition of the pilot and passenger in the machine, noting that if we use a heavy stagger we should use ailerons and not warp.

We have then data for the dynamic properties of model aerofoils and know how we can use them for calculations on full-size ones.

Let us turn to the consideration of the weight of aerofoils as a structure, for, unfortunately, they have got to lift their own weight first and then supply their surplus energy to lifting the rest of the machine.

WEIGHT OF AEROFOILS

For Similar Aerofoils — FIG. 8

Let w = wgt in lbs/□'

A = Area in □' & L = length of Chord in feet

Then wA = weight of aerofoil & $\propto L^3$

$\frac{W_T}{A}$, $\frac{\text{Total weight of Machine}}{\text{Area of aerofoils}}$ = Mean Total Loading in lbs/□'

So $\frac{W_T}{A} - w$ = useful loading in lbs/□' & = Load for Stress

If $\frac{W_T}{A} - w$ = constant then for same strength

$$wA \propto L^3 \quad \text{or} \quad w \propto L \quad \text{or} \quad w \propto \sqrt{A} \quad \text{or} \quad w = k_1\sqrt{A} \quad \text{(i)}$$

For aerofoils of same strength & same Area

$$k_1 \propto \frac{W_T}{A} - w \quad \cdots \quad \text{(ii)}$$

From previous Data

If $\frac{W_T}{A} - w = 5$ lbs/□' then $k_1 = \cdot 07$

Hence, from (ii), — $k_1 = \cdot 014\left(\frac{W_T}{A} - w\right)$

& hence, from (i), — $w = \cdot 014\left(\frac{W_T}{A} - w\right)\sqrt{A}$ in lbs/□'

Equation for wgt of Aerofoils

(Fig. 8.) Similar structures will bear the same ultimate load per unit area, which means in our case that similar aerofoils will have the same "factor of safety" for the same value of *useful* loading in lbs. per square foot.

Taking basic figures from actual satisfactory aerofoils, we shall assume that we can construct an

aerofoil of 100 sq. ft. surface, to weigh 70 lbs., and to stand 5.7 lbs. per sq. ft. total loading with the margin of strength necessary. This figure for weight, i.e., .7 lbs. per sq. ft., includes the weights of stays for a monoplane and of stays and struts for a biplane. Now we consider the aerofoil as stressed only by the useful loading, i.e., total load, W_T, minus aerofoil weight, since in flight it is stressed only by the lift it exerts over and above its own weight. We shall take it then that since the weight of similar aerofoils varies as the cube of the linear dimension and the surface as the square, the weight per sq. ft., w, will vary as the square root of the total surface, A, for the same unital useful loading, or value of $\frac{W_T}{A} - w$.

Further, we shall take it that for aerofoils of the same total area, within the limits of useful loading desirable to employ, the weight per sq. ft., w, varies directly as the unital useful loading $\frac{W_T}{A} - w$, for the same strength.

We see that on these assumptions for a total surface of 100 sq. ft. the weight per sq. foot will be .7 lbs. for 5 lbs. per sq. ft. useful loading, but for a total surface of 400 sq. ft. it will be 1.4 lbs. for the same useful loading. This is one of the basic facts against the building of large sized machines; for unless we can improve our structure (and of course the larger the machine the better chance we have of so doing) the greater must the proportion of aerofoil weight to useful load become.

We have then, that since

$$w = k_1 \sqrt{A} \text{ lbs. per sq. ft., and}$$

$$k_1 = .07 \text{ when } \frac{W_T}{A} - w = 5.0 \text{ lbs. per sq. ft., and}$$

$$k \propto \frac{W_T}{A} - w \text{ (useful loading)}$$

therefore $k_1 = .014 \left(\frac{W_T}{A} - w\right)$

and therefore

$$w = .014 \sqrt{A} \left(\frac{W_T}{A} - w\right) \text{ in lbs. per sq. ft.,}$$

an equation for the weight per sq. ft. of our aerofoils, in terms of total aerofoil area and total weight of aeroplane.

ITEM WEIGHTS .. FIG. 9

(i) Weight of Tail unit, i.e. of Tail Plane, Elevators, Rudder & Fin (if used)

$$w_T = \frac{1}{5} \text{ total Aerofoil wgt} = \frac{1}{5} w \cdot A$$

(ii) Weight of Body, w_B —

If l, b & d represent respectively length, mean breadth & mean depth of Body in feet

then $w_B \propto l^2 \times b \times d$

& if $l = 20$ ft, $b = 2$ ft, $d = 2$ ft then $w_B = 90$ lbs

Hence $\underline{w_B = \cdot 057\, l^2 \cdot b \cdot d \text{ in lbs}}$

(iii) Weight of Seating = 10 lbs per person

(iv) Weight of Controls = 30 – 50 lbs, dependent on type.

(v) Weight of landing gear complete, w_G —

$w_G = \frac{1}{14} W_T$, of this wgt. of Tail Skid = $\frac{w_G}{20}$

ITEM WEIGHTS

We must now get figures for our other weights. (Fig. 9.)

Generally speaking, the size of the Tail, Rudder, and Vertical Fin (if used) will vary directly as the size of the Wings (this assumes, of course, approximately constant proportions for the machine). I suggest, then, taking the necessary weight of Tail and Rudder and Fin as a proportion of the aerofoil total weight, and a fair figure to take is one-fifth.

The weight of the body introduces the question of the number of people the machine is to carry. A sufficiently strong body of the timber and wire, fabric covered, girder type can be made, of about 20 ft. length and 2 ft. mean breadth and depth, to weigh about 90 lbs., i.e. if $l = 20$ feet, b and $d = 2$ feet then $w_B = 90$ lbs.

Since in such a structure the struts are (generally speaking), very strong compared to the fore and aft members, for the kind of stresses to which it is subjected, we shall assume that the weight will vary directly as the breadth and depth, but as the square of the length. Hence, we get an equation for weight of Body $w_B = .057\, l^2\, b\, d$ in lbs.

As for the contents of this body. We can seat each person properly for about 10 lbs., and the weight of control mechanism will be from 30 lbs. to 50 lbs., dependent upon the type employed.

It remains only to consider the weight of suitable landing gear. I think it fair to consider the weight of the Landing Gear, w_G, as varying directly as the total loaded weight, w_T, of the machine, and I think a suitable one can be designed at one-fourteenth of the total loaded weight. This weight we shall take as including the weight of the Tail Skid. For an average landing gear and tail skid we may consider weight of Tail Skid alone as $= 1/20$ of total weight of Landing Gear.

FIRST ESTIMATES

We are now in a position, having been given certain requirements, to make a first estimate of weights, deciding in so doing upon the motor to employ.

The designer is generally required to produce a machine to carry a certain number of people, petrol and oil for so many hours' flight at full power, a certain weight of observing instruments, perhaps some weapons of offence, fully loaded to be able to fly at not less than a certain maximum, and not more than a certain minimum speed, and to climb at not less than a certain minimum rate.

Probably the simplest course to take in this brief outline of designing methods is to assume a certain set of conditions has been given and see how we should set about trying to fulfil it. We shall assume, therefore, that we are asked to design a machine to carry two people, pilot and passenger, to fly at 80 m.p.h. maximum and 40 m.p.h. minimum, to climb at 7 feet per second fully loaded, to carry petrol and oil for 4 hours to have a good range of view downwards for the passenger, to carry a full outfit of instruments, i.e., barograph, compass, map case, watches, engines revolution counter, air speed indicator, inclinometers, etc.

We must, of course, keep everything as small, compact and simple as possible to maintain strength and avoid weight.

To keep the fuselage weight and head resistance as low as possible we shall make it a tandem-seated machine.

As a good downward view is required for the observer, we shall seat him in front of the pilot as far forward as possible.

As the machine must necessarily be of a fair total weight and of fairly light loading to fly at the necessary minimum speed, we shall make it a biplane.

Further, we shall give it sufficient stagger for the observer to be able to see vertically, or nearly vertically, down over the leading edge of the lower aerofoils.

This will probably mean a rather large stagger, so we shall decide on ailerons for lateral control, these having the further advantage over warping that they give much better control power at low speeds (which entails, of course, large values of i). Warping is equivalent to increasing the i value of one aerofoil tip ; at slow speeds this may mean *no* increased lift, as the machine may already be flying with its aerofoils at their attitude for maximum lift, but it *will* mean increased drift with tendency to spin in the wrong direction. But pulling down an aileron is equivalent to increasing the camber of part of the aerofoil, and, hence, will give increased lift at any value for i.

We shall make the Body 20 feet long by 2 feet mean depth and breadth, and, therefore, of 90 lbs. weight, the weight decided on before for this particular size.

We must allow 350 lbs. for pilot and passenger in their flying kit, and 20 lbs. for seating them.

The controls, being not dual and being for ailerons, we shall take at the lightest weight, 30 lbs.

For the full kit of instruments called for we must allow 30 lbs.

This gives us a total weight of Body and contents of 510 lbs.

We now come to rather an impasse, as we cannot get weights of Aerofoils, Tail Unit and Landing Gear until we have fixed on the engine, and we should like to know the total weight in order to fix on the engine. So we must make a first choice of an engine, judging from some previous machine.

We know that with the 80 Gnome one can make a tractor biplane to fly at 40 to 78 m.p.h. with 4 hours' fuel and oil, pilot and passenger, and climb at about the rate we require. We shall, therefore, need more power than the 80 Gnome for our machine ; but, of course, we want to use as low a power as possible.

Let us try the 80-p.h. Le Rhone. From our weight table for engines we find that total weight for this motor with 4 hours' petrol and oil, tanks, mounting, cowling and propeller will be 726 lbs.

We now have total weight less Aerofoils, Tail Unit and Landing Gear = 1,246 lbs. There remains to fix on wing form and loading, and thence Wing, Tail Unit, and Landing Gear weights.

The total weight W_T will be equal to 1,246 lbs. $+ w_G + (w \times A) + (1/5\, w \times A)$ (Fig. 10), where w_G = weight of Landing Gear, including Tail Skid, w = weight of Aerofoils in lbs. per square foot, and A = total surface of Aerofoils in square feet. The $1/5\, wA$ is, of course, the Tail unit weight.

Further we have that $w_G = 1/14\, W_T$—

Hence, $13/14\ W_T = 1246 + 1.2\ wA.$ (1)

ESTIMATE FOR TOTAL WEIGHT ETC — FIG. 10

Total weight $W_T = 1246 + w_G + wA \pm \frac{1}{5} wA$ (lbs)

Whence – $\frac{13}{14} W_T = 1246 + 1\ 2\ wA$ (lbs) (I)

Taking $U_{(min)} = 58$ fps –

For $\frac{W_T}{A} = 4$ lbs/□'	$K_{y(max)} = \cdot 00119$	For Biplane
" " 4·5 "	" = ·00134	
" " 5·0 "	" = ·00149	
" " 5·5 "	" = ·00164	

Taking $U_{(max)} = 120$ fps

$$\frac{K_y \text{ for } 120 \text{ fps}}{K_y \text{ for } 58 \text{ fps}} = \frac{58^2}{120^2} = \cdot 233$$

Taking K_y biplane with Gap = 1·0 Chord & Stagger = ·4 Chord

K_y Biplane = ·85 K_y Monoplane

Hence necessary Model Monoplane figs –

For $\frac{W_T}{A} = 4$ lbs/□'	K_y at 58 fps = ·00140
" " 4·5 " "	" " " " = ·00158
" " 5·0 " "	" " " " = ·00176
" " 5·5 " "	" " " " = ·00193

K_y for 120 fps = ·233 of above values

If K_y max = ·0015 loading = 4·3 lbs/□' at 58 fps

If $W_T = 1900$ lbs & $\frac{W_T}{A} = 4{\cdot}3$ lbs/□' then $A = 440$ □'

From Equation $w = \cdot 014\sqrt{A}\left(\frac{W_T}{A} - w\right)$

$w = \cdot 014\sqrt{440}\,(4{\cdot}3 - w)$

or $w = \cdot 98$ lbs/□'

& $w \cdot A = 430$ lbs (II)

Hence from (I) & (II)

$\frac{13}{14} W_T = 1246 + (1{\cdot}2 \times 430)$ or $W_T = 1900$ lbs

CHOICE OF AEROFOIL

We must now fix upon what form of aerofoil to employ and what loading.

The first thing to note is that the machine has to be able to fly at 40 m.p.h., or about 59 f.p.s. So the maximum Ky value for the aerofoils must be such as to give us lift per square foot at 58 feet per second equal to the total loading per square foot that we shall choose.

This may seem a small margin to allow for obtaining the slow speed, but it must be remembered, that at the slow speed, and consequent cabre, or tail-down, attitude of the machine, there will be a certain amount of added lift from the tail and body of the machine, and a slight upward component of propeller pull.

Also we must cut the slow speed as fine as possible to get the greatest possible high speed.

Now, for 4 lbs. per square foot, total loading at 58 feet per second maximum Ky must be = .00119.

For $4\frac{1}{2}$ lbs. max. Ky must be = .00134.

For 5 lbs. max. Ky must be = .00149.

For $5\frac{1}{2}$ lbs. max. Ky must be = .00164.

All these being values for a biplane, of course.

We must now consider our high-speed:

The high speed is to be 80 m.p.h., or 117 feet per second. Considering it as 120 feet per second we see, of course, that the Ky values for this speed must be $\frac{58^2}{120^2}$ of the Ky values for 58 feet per second, as loading is constant. That is to say:

Ky at 120 f.p.s. must = .233 Ky at 58 f.p.s.

CORRESPONDING MONOPLANE VALUES

We must next, as our machine is a biplane, and our figures for model aerofoils are for single or monoplane form, obtain from our tables for effects of gap and stagger the necessary corresponding monoplane Ky values. We shall assume that we shall make gap = chord and stagger = about .4 of chord. We shall, therefore, as sufficiently accurate for the present, take that Ky biplane = .85 Ky monoplane, as it would be about .82 for this gap and no stagger, and we obtain about 4 per cent. increase of efficiency due to the stagger.

That is to say, the necessary biplane Kys we have found for different loadings, must be multiplied by 1.18 for monoplane tests. We get then :

For—

4.0 lbs.	per sq.	ft.	loading	Ky max.	must be	.00140
4.5	"	"	"	"	"	.00158
5.0	"	"	"	"	"	.00176
5.5	"	"	"	"	"	.00193

and Ky high-speed = .233 of these values as we saw before.

We turn now to our data sheets for Model Monoplane Aerofoils and fix upon the best form for our case.

We have to pick out that Aerofoil which, having a maximum Ky of .00140 or over, will give us the highest value for Lift to Drift for a Ky value = .233 of its maximum value ; that is, we must consult the curve of Ky value, and the curve of Lift to Drift on a base of Ky value, for all our data sheets, and pick out the best Aerofoil for this case.

We shall assume that we have done this and have found the best Aerofoil form for us to be one which for a maximum Ky of .0015 gives us, at Ky = .233 of .0015 (or .00035), a Lift to Drift of 10/1.

With this Aerofoil we must have a loading of 4.3 lbs. per square foot.

We must now make a shot at the total weight W_T, as we shall then be able to get a figure for total Aerofoil Area, thence for Aerofoil weight, thence a figure for total weight, which must be very nearly the same as our guessed weight, or we must guess again with increased wisdom.

We shall guess, then, that the machine is going to weigh, fully loaded, 1,900 lbs., and it will, therefore, need $\frac{1900}{4 \cdot 3}$, or 440 square feet of Aerofoil surface at the 4.3 lbs. per square foot total loading.

From our previously determined equation:

$$w = .014 \sqrt{A} \left(\frac{W_T}{A} - w \right)$$

$$\text{We get that } w = .014 \sqrt{440}\,(4 \cdot 3 - w)$$

$$\text{whence } w = .98 \text{ lbs. per sq. ft.}$$

This, then, gives us Aerofoil weight = 430 lbs., and we get that $\frac{13}{14} W_T = 1762$, or $W_T = 1900$ lbs.; of this, Tail unit weight is 86 lbs., Landing Gear Weight = 136 lbs., and of this, again, 7 lbs. is Tail Skid.

This is our guessed weight (I admit that I guessed once or twice in getting out these figures, but have spared you the tedium by quoting the right guess at once); so we can take the figures for total weight and wing surface as found.

DEFINITE DESIGN

We have now fixed weights, surface, aerofoil form and motor, and can proceed with the design.

We shall, as this is a largish machine, choose an aspect ratio of 6 to 1, which gives us 4 aerofoils of 6.15 feet chord by 17.5 feet " mean " span, which, with the top centre plane of 2 feet span, gives us a total " mean " span of 37.0 feet, and our total surface (which is surface of 4 aerofoils + top centre plane), of 440 square feet. I talk of " mean " span, as we shall employ ends raking at 20° for our aerofoils.

We must now draw out a side elevation of the body of the machine with seats, tanks, motor, and tail skid, keeping all the weights as close together as possible. (Fig. 11, page 46). We shall employ a " non-lifting " Tail plane, that is to say, a form symmetrical about its central horizontal plane and with this plane parallel to the axis of the propeller.

This form is perhaps the safest to employ, as it will give no difference in lift or depression, whether in the propeller slip stream (when the motor is running) or not (when the motor is stopped). We shall set the chord of the aerofoils at 3° to the propeller axis.

We now require to place our Aerofoils and Landing Gear, less Tail Skid, of course, on the body in such a manner that the total reaction on the Aerofoils, at 3° value for i, passes through the CG of the whole machine (of this more anon), and

Fig. 11.

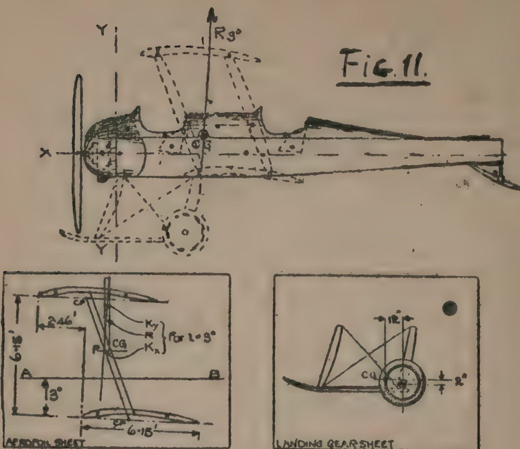


TABLE FOR HORIZONTAL & VERTICAL C.G

ITEM	W	l	h	W×l(+)	W×l(−)	W×h(+)	W×h(−)
Propeller	28	+2·0	–	56	–	–	–
Motor	250	+·7	–	175	–	–	–
Cowling	32	+·4	+·4	13	–	13	–
Motor Mounting	36	−·2	–	–	7	–	–
Oil & Tank	86	−·6	+1·3	–	52	112	–
Passenger	175	−2·5	+1·0	–	390	175	–
Passenger's Seat	10	−2·8	+·4	–	28	4	–
Petrol & Tank	294	−5·2	+1·4	–	1530	412	–
Body	90	−6·7	–	–	602	–	–
Instruments	30	−7·1	+1·5	–	213	45	–
Controls	30	+7·5	–	–	225	–	–
Pilot	175	−8·7	+1·0	–	1520	175	–
Pilot's Seat	10	−9·1	+·4	–	91	4	–
Tail	86	−19·0	+1·0	–	1630	86	–
Tail Skid	7	−19·7	−1·0	–	138	–	7
Aerofoils complete	430	−4·9	+2·8	–	2107	1208	–
Landing Gear	129	−2·5	−3·9	–	322	–	503
TOTAL (loaded)	1898	−4·55	+·91	244	8855	2234	510

W = wgt of Item in lbs
l = Normal distce of CG of Item from line Y-Y. + ahead, − behind
h = " " " " " " " X-X + above, − below

that the centre of the wheel axle of the Landing Gear is about 12″ ahead of it.

This, of course, is another trial and error process, and had best be arrived at as follows :—Draw on a piece of tracing paper the side elevation of the Aerofoils (to same scale as Body, of course), with correct gap and stagger, also a base line AB inclined at 3° to the chords. From model figures for the Aerofoil form mark on chord of each Aerofoil the position of Centre of Pressure with i = 3° ; join these two points by a straight line, and on this line mark a point P, 4/7 of its length from the chord of the lower Aerofoil ; through this point P draw a line perpendicular to the aforementioned base line AB. This line we can take as representing accurately enough the line of Lift reaction on our *biplane*, for i = 3°. Through this same point P draw a line parallel to the Base line AB, which will represent the line of Dynamic Resistance of our biplane for i = 3°.

From the figures for our Aerofoil form, we shall measure off, to some suitable scale, a distance from P on the Lift re-action line to represent our biplane's Ky value i at = 3° and a distance from P on the Dynamic Resistance line to represent our biplane's Kx value at i = 3°. By drawing a parallelogram and its diagonal through our chosen point P, we now get a line (this diagonal), which represents the line of Total Re-action on our Biplane at i = 3°.

Note that we take 4/7ths of the inter Aerofoil distance, not ½, for the top aerofoil does more work than the lower, in about the proportion of 4 to 3, at small values for i.

To same scale we must draw on another piece of tracing paper a side elevation of the Landing Gear.

We must now place these over our body drawing in guessed positions, keeping the base line AB on the Aerofoil drawing parallel to the axis of motor, and proceed to make a first calculation for position of CG. For this calculation we shall take horizontal Moments about the fore end of the body, and vertical Moments about the axis of the motor, as convenient datum lines, taking the weights of the various items multiplied by the normal distances of their CGs from these datum lines. We can fix pretty accurately the CGs of the items. I suggest taking the CG of the Aerofoils as slightly above the centre of a line joining the centre points of the lines which join the centre points of the spars of top and of bottom Aerofoils; slightly above (say 11/20ths above bottom), because the centre plane and its struts are at the top of the whole structure. The CG of the body alone may be taken as about 1/3 of its length from its fore end; the CG of the Tail unit as about 1 foot ahead of the rear end of the body; the CG of the Landing Gear, assuming a form as shown, as lying 12″ ahead of, and 2″ above, the wheel centres; the CG of a man sitting as about 12″ ahead of the seat back and 12″ above the seat bottom.

The CGs of the other items, tanks with petrol and oil, engine, engine mounting, engine cowling, seats, controls, instruments, Tail Skid, etc., are easy to fix accurately enough by inspection.

If our first shot for Aerofoil and Landing Gear position be out we must slide them to new positions, and try again, till we get the positions which answer our requirements.

We have now fixed up our outline design, and it remains to consider strength and stability, and then to finally check whether we have sufficient power for the high-speed and for the climb.

But before passing on let us note that the tank positions must be such that the CG alters little in horizontal position, whether they be full or empty, and they must also, of course, be of the required capacity. As it is almost impossible to keep the CG of both petrol and oil over the CG of the whole machine, and since for our motor the weight of petrol consumed per unit time is about six times the weight of oil consumed per unit time, we should keep the CG of the oil about six times as far (horizontally) from the total CG as is the CG of the petrol, and, of course, the tanks on opposite sides of the total CG.

Bearing this in mind, we get in the tanks as best we can.

WING STRENGTH

For the strength of the wings, considered as an ordinary framed structure, we now have the overall sizes, the position of main aerofoil spars and of struts and ties. Considering each spar as a continuous beam and each aerofoil as uniformly loaded (its own weight being of course now *not* taken) for 5/6ths of its mean length, we must find the curve of bending moments and the reactions at the supports of each spar, firstly with the centre of pressure at its position nearest to the leading edge, and secondly at its position for full speed, which will be much further from the leading edge. The sections and materials of the spars must be chosen such that under neither of these conditions do the maximum calculated fibre stresses exceed 1/6th of the ultimate compressive strength of the material employed. This is the so-called "factor of safety" generally called for.

Similarly the cross sections and material for each strut must be so chosen that (for a form of low head resistance), the maximum applied load does not exceed 1/6th of the ultimate strength, calculated by Euler's formula for a pillar pin jointed at both ends.

Similarly each stay cable should have an ultimate strength, taking into account any weakening due to splicing, etc., of at least 6 times the maximum pull we shall, from the before-mentioned calculations, find it subjected to.

I suggest considering the aerofoils as uniformly loaded for 5/6ths only of their total lengths,

because, owing to end losses, the loading decreases towards the outer ends, and this assumption therefore gives a fairly accurate and a simple method of accounting for the actual distribution of loading over the aerofoil surfaces. Of course the uniform loading used for the calculation must be adjusted so that total loading remains equal to the total weight for stress.

I shall not touch further on strength except to say that the same requirements hold throughout the machine, and the unfortunate designer is expected to be able to produce reasonable figures showing that his detail design is such that no part of the machine has a "factor of safety" of less than 6 under such condition, between slowest and fastest flying speeds, as imposes the greatest strain on such part.

STABILITY

Now to consider stability and controllability, which resolves itself for us into determining the size of Tail Plane, Elevator, Fin, and Rudder and amount of dihedral angle of the Aerofoils for our design.

The full investigation of the stability of an aeroplane is necessarily an extremely long and difficult process, involving mathematics of a high order. I do not propose, however, to consider anything other than a few very simple methods in which by using data from model experiments and quite elementary mathematics we should arrive at decently satisfactory results. Thus, though they are all more or less interdependent, I propose to consider longitudinal or "pitching stability," lateral or "rolling stability," and directional or "yawing stability" separately. Further, I shall take no account of the moment of inertia of the machine, though this has effects on the stability, except to state that the moment of inertia about all three axes should be kept as low as possible, as much from strength as from stability considerations. A machine of large moment of inertia may perhaps be made as stable as one of small, but, inasmuch it will rotate more slowly about any axis, it is highly probable that it will be subjected to greater local stress in a fluctuating wind, and it will answer more slowly to, and is therefore more likely to be locally stressed by, its controls.

LONGITUDINAL STABILITY

First, then, for " longitudinal stability," and by this I mean an innate tendency of the machine to preserve a constant attitude to its flight path—that is, to preserve a constant value of i for the aerofoils. For us this resolves itself into a determination of the size of the tail plane and elevators.

As you will have noted from our preceding curves for aerofoils, all along the range of i values useful for flight a curved aerofoil is unstable—that is, as i increases the CP moves forward, as i decreases the CP moves backwards ; in both cases, therefore, the shift of CP tends to aggravate and not to stop the alteration of i value.

Similarly, the body, which for low head resistance generally approaches a torpedo form, is instable for small angles to its flight path. It is left to the tail, therefore, to counteract the inherent instability of aerofoils and of body.

As for the form of calculation, this is best set out in tabular form (Fig. 12, page 54). In column 1 we have a values, a being the angle which the *axis of the motor* makes with the direction of flight ; in column 2 the corresponding values for i, which for our case will be $a + 3°$ throughout ; in column 3 corresponding values for K_Y, the lift coefficient of the aerofoils ; in column 4 corresponding values for K_X, the drift coefficient of the aerofoils ; in column 5 values for total reaction coefficient R, which is, of course, $= \sqrt{K_Y^2 + K_X^2}$; in column 6 values for A × R, or aerofoil surface multiplied

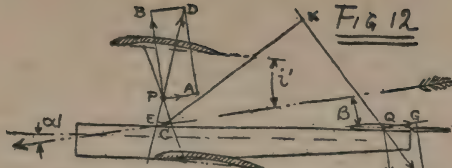
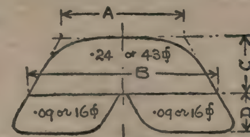


FIG 12

PB = K_y for i'
PA = K_x " "
PD = R " "
CE = L " "

QF = k_y for β'
QG = k_x " "
QH = r " "
CK = l " "

CALCULATION FOR SIZE OF TAIL.



Ratios { ☐ = ·42 or 75 ☐' ; B = 1·00 " 13·3 ; A = ·66 " 8·8 ; C = ·30 " 4·0 ; D = ·20 " 2·76 } ft } for M/C

$\alpha°$	$i°$	K_y	K_x	$R = \sqrt{K_y^2+K_x^2}$	A×R (A=440 ☐')	L	A×R×L	β	k_y	k_x	$r = \sqrt{k_y^2+k_x^2}$	l	$r \times l$	$\frac{A \times R \times L}{r \times l}$
-5	-2	·00007	·000051	·000086	·0378	−2·10	−·0794	-5	−·00044	·00011	−·00045	+13·7	−·00616	12·9
-3	0	26	38	263	·1160	− ·70	−·0812	-3	−·00027	·00009	−·00029	+13·5	−·00392	20·7
-1	+2	46	37	461	·2030	− ·20	−·0406	-1	−·00009	·00008	−·00012	+10·7	−·00109	37·2
+1	4	64	43	641	·2820	+·04	+·0110	+1	+·00009	·00008	+·00012	+10·7	+·00109	10·1
3	6	83	63	·832	·3660	·17	·062	3	27	9	29	+13·5	·00392	15·8
5	8	102	89	1030	·4630	·30	·139	5	44	11	45	+13·7	·00616	22·6
7	10	120	124	1206	·5300	·36	·191	7	61	113	62	+13·6	·00843	22·7
9	12	136	163	1370	·6030	·42	·253	9	78	15	79	+13·5	·01068	23·7
11	14	147	205	1485	·6530	·41	·268	11	94	18	96	+13·3	·01279	21·0
13	16	150	250	1520	·6690	·40	·268	13	110	22	112	+13·2	·01479	18·1

by total reaction coefficient ; column 7 is for L values, L being the perpendicular distance from CG of machine to line of action of R.

Column 8 is for A × R × L values, which is a function of the moment of the reaction on the aerofoils about the CG ; in column 9 we have values of β, or inclination of *tail plane* to line of flight, in our case $\beta = a$ throughout ; in column 10 corresponding values of kY for *tail plane ;* and in column 11 corresponding values of kX for *tail plane ;* in column 12 values of total reaction coefficient r on tail plane, r being, of course, $= \sqrt{kY^2 + kX^2}$; column 13 is for values of l, perpendicular distance from CG of machine to line of action of r ; column 14 for values of r × l ; column 15 is for values in column 9 divided by values in column 16—i.e., for $\frac{A \times R \times L}{l \times r}$ —and this gives us the required tail area necessary to just counteract the moment of reaction on the aerofoils, *assuming the tail as in undisturbed air.*

If we can get accurate model figures for the air reactions on the body of our machine we should get out a second table, similar to the foregoing, to find the necessary area of the tail plane to counteract the instability of the *body*. But as we may not have these figures, and as the reaction on the body is comparatively small for a narrow form such as we are using, we may, in the absence of reliable model figures, neglect the second table, and merely add a small amount to the tail surface necessary for the aerofoils alone—say 1/10th.

As to how the figures for columns 7 and 13 are arrived at, in a similar manner to that in which we drew the line of total reaction on our biplane for $i=3°$, we must draw a series of lines representing lines of total reaction on it for each of the i values in the table. We can then on our side elevation drawing measure the perpendicular distances from CG of machine to each of these lines, these distances being values for L, to scale of drawing. On the figure I have, for clearness, only drawn line for R at 1′ value for i.

As for the tail plane, assuming we shall decide to employ one of the form shown, as a good compromise between strength and efficiency, if we have not figures for a model of this form it is probably accurate enough to take for it figures for a rectangular plane of aspect ratio 2 to 1.

As we do not know until after the calculation the size for our tail plane, we do not know exactly the position of its line of reaction. But the chord of the tail plane is fairly small compared to the distance from CG of machine to centre of pressure or tail plane, and smaller still is the *shift* of CP on tail plane compared to this distance. Hence we shall assume a point, say, 2 ins. above the top of the body and 2 ft. from the rear end of the body as the position of C of P on tail plane, and shall neglect the shift of CP. Of course, if on finishing the calculation we find that, for the tail plane size which we shall need, our guess is obviously a lot out, we must alter up and correct our table.

We shall take the required area of tail for our machine—that is to say, area of tail plane plus

area of elevators—as twice the greatest area called for in the table. This seems rather a libel on our calculations, but the reason for this apparent large excess of tail area is that the tail is acting both in the down-draught from the aerofoils and—when the engine is running—in the slip-stream of the propeller ; both of these factors tend to *decrease the alteration of air flow relative to the tail*, when the attitude of the whole machine to its flight path is altered. That is to say, they both tend to decrease the correcting power of the tail.

This figure of half-value for the tail on the machine to Tail considered as in undisturbed air is approximately that found by recent experiments at the N.P.L.

Before leaving the question of longitudinal stability I would suggest that the value of total area of tail should be kept about as it would be found by the foregoing calculations for *any* machine, but the more the power of control required the greater should the relative area of elevators to tail plane be made. The ratio of elevator area to tail plane should lie between the limits of .6 to .4 and .3 to .7. Outside these limits we shall get a machine either heavy on the controls on the one hand, or slow to respond on the other. We shall use, therefore, a total area of 75 sq. ft., of which .43, or 32 sq. ft., is in the elevators, and we arrive at the sizes as shown.

DIRECTIONAL STABILITY

Very briefly, for " directional " or " yawing stability," for us this now means size of rudder and fin required. I say rudder *and* fin for our machine, as I think it is safer to use a fin on large and heavy machines. On small and light machines it is perhaps not necessary. Structurally, of course, the employment of a fin is of value.

We have at present few figures on which to base calculations for rudder size. The rudder and fin considered as a fixed surface must be large enough to counteract the inherent yawing instability of the body, also to counteract the yawing effect of the side surface of those parts of the landing gear which are ahead of the CG, and also to counteract the yawing effect of the propeller considered as a front fin.

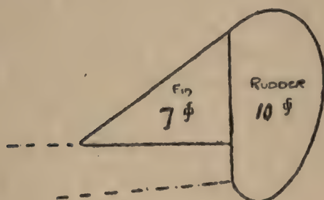
We must also be sure that, when the rudder is set at about 5 degrees, say, it has ample power *additionally* to counteract the worst spinning moment induced by working the warp or ailerons. Unless we have model figures for yawing moments on the fuselage, and for drift on an aerofoil with ailerons at different attitudes, we had better determine our rudder area from figures for other machines as nearly like ours as possible which we know were satisfactory as regards their directional stability and control.

I suggest, then, using an empirical formula (Fig. 13):

$$C\,(s \times d) = S - \frac{S \times D}{2} + A$$

in which s = area of rudder in sq. ft., d = distance of centre of area of rudder from CG of machine in feet, S is area of side elevation of body, aerofoils, landing-gear, and propeller in sq. ft., D = distance of centre of this area S *behind* CG, A is area of aerofoils in sq. ft., and C is a constant which we shall take as 1.7, from figures for other machines of this type.

Fig 13



The value for body side area is the area *in side elevation* of body, complete with all added top superstructure, cowling round motor, etc.

The value for side area of aerofoils is that of the aerofoils with their struts in side elevation, thus taking account of the fin area due to dihedral.

In our case, then, we have

$$1.7 \times s \times 15 = 70 - \frac{70 \times 2.4}{2} + 440 \text{ or } s = 17$$

That is, we require a rudder + Fin area of 17 sq. ft. We shall dispose this in a form as shown in Fig 13.

LATERAL STABILITY.

Let us consider the causes for possession of, or lack of, " lateral stability " in an aeroplane. An aeroplane is a body immersed in a fluid—air —and since its average density is very great compared to that of air, we consider it as supported only by the reaction of the air upon its lifting surfaces. That is to say, it is supported solely by reason of its speed relative to the air.

Now, for both of the stabilities we have already discussed—that is " pitching " stability and " yawing " stability—the flight path is approximately at right-angles to the axes of rotation. Hence a small rotation immediately induces a change of reaction upon the tail plane, or rudder, as the case may be, which tends to counteract the rotation. But when we come to consider the third form of stability—that is, " lateral " or " rolling " stability —we see that the rotation now takes place about an axis which is parallel, or very nearly parallel, to the flight path.

Hence rotation about the longitudinal axis, or rolling, will *by itself* produce no change whatever upon the air reactions on the machine ; that is to say, if an aeroplane rotate about an axis parallel to its flight path, *no other motion being present*, no force is created to counteract the rotation.

However, when an aeroplane rolls, other movements do occur, and it is from these that we attain " lateral stability."

Let us consider, then (Fig. 14), an aeroplane

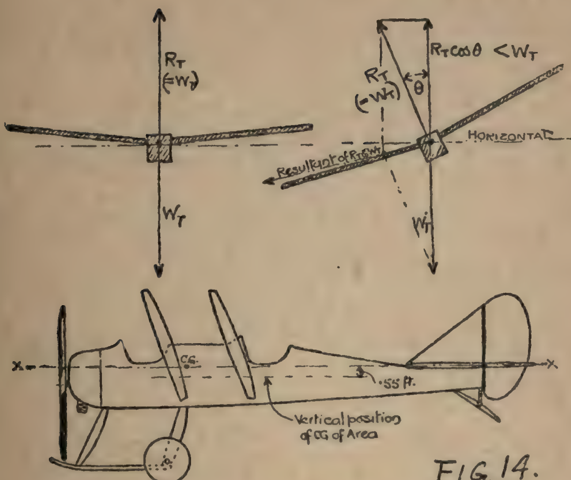


FIG. 14.

CALCULATION TABLE FOR VERTICAL C.G. OF AREA

ITEM	A (□')	h (ft.)	A×h.
Propeller	2·5	− ·9	− 2·2
Cowl	4·0	− ·5	− 2·0
Chassis Front Strut	1·0	−3·6	− 3·6
" Rear "	·8	−3·0	− 2·4
" Skid	1·0	−5·2	− 5·2
" Wheel	3·8	−4·9	− 18·6
Body below x-x	36·0	− ·9	− 32·4
" above "	8·6	+ ·5	+ 4·3
Aerofoil Struts	4·8	+1·2	+ 5·8
Fin	6·0	+1·0	+ 6·0
Rudder	9·0	+ ·9	+ 8·1
Tail Skid	·6	−1·8	− 1·1
TOTAL	78·1	−·55	−43·3

A = side elevation Area of Item in □'.
h = distance of Centre of Area of Item above or below Axis x-x
+ Above
− below

flying steadily and horizontally and assume that some outside force, say a puff of wind, rolls it over slightly. We see that, as speed and therefore total reaction, RT, remain constant, and as the lift reaction is now out of line with the gravitational force, the vertical component of lift is now less than the gravitational force, and the horizontal component is unbalanced; that is to say, the machine will commence to drop and move sideways. Directly it commences to do this we *get* motion perpendicular to the axis of rotation and, if our surfaces are properly disposed, a righting moment therefrom.

Briefly, then, we see that, for "lateral stability," if the machine have a sideways velocity relative to the air, the resulting reactions on the whole machine must tend to raise the then leading aerofoil tip. This is the main reason why a dihedral angle for the aerofoils tends to give lateral stability. We also see that, if the outer shape of a machine remain the same, the higher the CG the greater the dihedral we shall need, and vice versâ.

It is necessary for us, therefore, to calculate the vertical position of centre of projected side area of the whole machine less the aerofoils. I then suggest that, if this centre of area lie at the same height as the CG, give 3 per cent. dihedral angle to the aerofoils. If the centre of area lie *above* the CG, less dihedral should be given; if *below* more dihedral should be given. For amount of increment (or decrement), I suggest 1° of dihedral per 15 value (in sq. feet × feet) of vertical moment of side area about CG. These figures are

quite arbitrary ones and I cannot vouch for their suitability. They approximately represent current practice for machines of this type.

As you will note, in our design the centre of projected side area is considerably below the centre of gravity, .55 ft.; so we had better decide to employ 5 per cent. dihedral angle.

We must note, before leaving the subject, that too much inherent stability should not be given to an aeroplane. "Inherent stability," as I have used it, being a tendency of the machine to retain the same attitude to its flight path or to its *relative motion to the air*, it follows that the more stable is a machine in this sense the more does it tend to follow alterations in wind direction, and this quality in excess makes for discomfort in flying and danger in landing. Hence we want to ensure that our machine has a *slight* margin of stability and that ample controlling power is afforded to the pilot to enable him to quickly alter at will its attitude in any direction.

PROPELLER THRUST

We have now got our design temporarily completed; it remains to calculate the head resistance as accurately as possible and the propeller thrust, to see if we have sufficient power for the required high speed and climb and to check the balance of the machine.

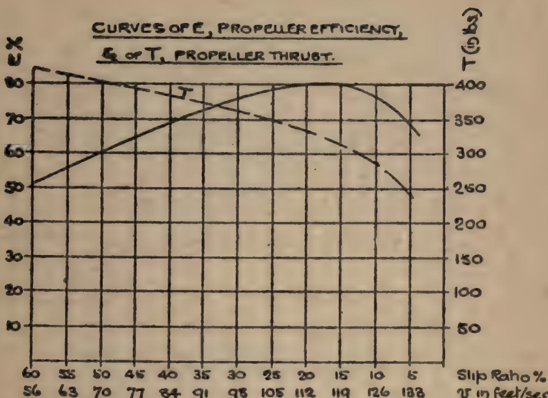
Firstly for the propeller thrust. I cannot attempt to touch propeller design in this paper; it is a subject for many papers in itself. I must merely refer to experimentally determined figures for propellers. We have a good many of these and can probably pick a form that will suit us. We will take it, then, that we have the curve of efficiency for a suitable propeller on a base of slip ratio at constant revolutions (Fig. 15).

The efficiency is expressed, of course, as—

$$\frac{\text{Useful work}}{\text{Total work}} \text{ or as } \frac{\text{Thrust} \times \text{speed}}{\text{H.P. given to propeller}}$$

The slip ratio is $\frac{(p \times r) - V}{p \times r}$ where p is pitch of propeller in feet, r revs. per sec., and V is speed, i.e., speed of advance along axis in feet per sec.

Knowing the horse-power our motor gives at full normal revs., we can from this efficiency curve make another curve of our actual propeller thrust in lbs. on a base of speed of advance, i.e., speed of aeroplane, in feet per sec.



$$E = \frac{\text{Useful Work}}{\text{Total}} = \frac{T \times v}{BHP \times 550}$$

Taking BHP = 85 — $T = E \times \dfrac{46750}{v}$ in lbs

$$\text{Slip Ratio} = \frac{(p \times n) - v}{p \times n}$$

Taking $p = 7$ feet
& $n = 20$ per sec — Slip Ratio $= \dfrac{140 - v}{140}$

FIG. 15.

HEAD RESISTANCE

It remains to get figures for plotting a curve of total head resistance (in lbs.) of machine on this same base of speed in feet per sec.

For this we turn to the front elevation of our aeroplane (Fig. 16) and determine which parts lie within the propeller disc and which outside it. The parts which lie *in* the propeller disc i.e., in the slip-stream from the propeller, will be in a current of fairly constant speed *irrespective of* speed of machine.

We make our calculation, therefore, in the form of two tables. The first table is for parts *in* the slip-stream, the second for parts *outside* it. In neither of these tables shall we include aerofoils, as the *total* reaction on these has already been dealt with in first balancing.

The coefficients for resistance for the different parts of our machine we must obtain from figures from model experiments, and of these we have a fair armament.

In both tables we find the resistance in lbs. for each item at some chosen fixed value of v ; at the same time we take, as you see, the moment of resistance of each item about the axis of the motor, vertically, of course, in order to obtain a figure for vertical position of centre of head resistance.

We must determine the vertical position of Centre of head resistance, less aerofoils of course, to see if there will be a thrust—head-resistance couple. If we find that there is one—that is to say, if the line of residual resistance is above or below

TABLE 1. In Slip Stream

ITEM	A.ф	K_x	R	h	R×h
Body	6·0	·0005	46·0	+·2	+9·2
Chassis Struts	1·30	·0002	4·0	-2·6	-10·4
" Cross bracing	·25	·0012	4·6	-2·6	-12·0
½ Axle	·45	·0002	1·4	-3·9	-5·5
Tail Skid	·40	·0004	2·5	-1·3	-3·2
Rudder	·40	·00008	·5	+2·4	+1·2
½ Tail & Stays	2·50	·00008	3·1	+1·0	+3·1
¾ Cr Plane Struts	·90	·0002	2·8	+3·0	+8·4
¾ " " Bracing	·15	·0012	2·8	+3·0	+8·4
R_1 (TOTAL)	12·35	·00036	67·7	-·01	-·8

$v = 124$ fps (130 − 5%)
$v^2 = 15{,}400$

$R_1 = K_x \times A \times v^2$ lbs
or $R_1 = 15400 K_x \cdot A$

FIG 16

TABLE 2 Outside Slip Stream

¼ Centre Plane Struts	·30	·0002	·6	+4·6	+2·8
¼ " " Bracing	·05	·0012	·6	+4·6	+2·8
½ Tail Plane	2·40	·00008	1·9	+1·0	+1·9
Aerofoil Cables	2·70	·0012	32·0	+2·4	+76·8
" Struts	4·00	·0002	8·0	+2·5	+20·0
½ Axle	·45	·0002	·9	-3·9	-3·5
Wheels & Shock absorbers	1·00	·00045	4·5	-3·9	-17·6
Skids	·30	·0006	1·8	-4·0	-7·2
R_2 (TOTAL)	11·20	·00045	50·3	+1·51	+76·0

$v = 100$ fps
$v^2 = 10{,}000$

$R_2 = K_x \times A \times v^2$
or
$R_2 = \cdot 00503 v^2$

At full speed i.e. 120 fps –

$R_1 = 67{\cdot}7$ lbs @ ·01 ft below line of Thrust

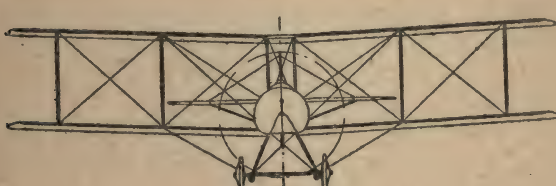
$R_2 = \cdot 00503 \times 120^2 = 72{\cdot}5$ lbs @ 1·51 ft above line of Thrust

Hence total Residual Resistance @ 120 fps

= 140·2 lbs @ ·77 foot above line of Thrust

When $i = 3°$, $v = 88{\cdot}5$ fps

Hence $R_2 = 39{\cdot}5$ lbs & Total Residual Resistance = 107·2 lbs @ ·55 ft above line of Thrust.



the line of thrust—we must either (if practicable) alter the line of thrust or, by slightly altering the fore and aft position of the aerofoils, introduce an equal and opposite lift-weight couple to counteract the thrust-head resistance one.

In the first of these tables, then, we shall take V as slightly below (say 5 per cent. below) the pitch speed of the propeller, and we shall take the total resistance R_1 of the items in this table as of the amount thereby found, and as constant for all speeds of the machine.

For our case we get R_1 as 67.7 lbs. acting .01 foot below line of thrust *and as constant.*

In the second table we shall take V as 100 f.p.s., being a convenient figure to work with, and the total resistance R_2 obtained is, of course, the resistance of all parts, except aerofoils, *outside* the slipstream at 100 f.p.s. We take R_2 as *varying as* V^2.

In our case, therefore, we get a second table resistance R_2 of 50.3 lbs. at 100 feet per sec.—that is to say, $R_2 = .00503\ v^2$ lbs. and acts 1.51 ft. *above* line of thrust. We see then that for the design as so far got out the line of total residual resistance is going to be considerably above the line of thrust. At maximum speed required, 120 f.p.s., it is going to be 140.2 lbs. acting .77 foot *above* the line of thrust. So we must either raise the line of thrust or shift the aerofoils aft slightly. We should, however, make the necessary correction for balance, for that speed at which i for aerofoils = 3°, as then the tail is floating.

Now when $i = 3°$, $Ky = .00055$, hence v must be 88.5 feet per sec., thence $R_2 = 39.5$ lbs., and

thence *total residual resistance* $R_2 + R_2 = 107.2$ lbs. and acts at .55 ft. above line of thrust. We shall therefore decide to shift our line of thrust up .6 foot, which will give a satisfactory balance and will have the additional advantages of bringing the line of thrust nearer to the CG and of slightly cutting down landing gear height, and therefore weight and head resistance.

We *should* now correct our tables for CG and for residual head resistance; this would be a repetition of the previously described calculations, and the figures for amount of total residual head resistance which we have already obtained would hardly be altered, certainly not *increased*, by this raising of line of thrust. Hence, as we can use them as they are for looking into the remaining points, I omit, for the sake of brevity, correcting up these tables here.

Finally, then, we turn again to our model aerofoil figures to obtain the remaining part of the total head resistance, the "drift" of our aerofoils (Fig. 17, p. 70). From the Ky values we first determine the speeds corresponding to several different values for i, say for i = 1°, 4°, 7°, 10°, 13°, 16°.

Taking into account the variation of lift to drift with log AV before quoted, we find then the drift (RD) of our machine's aerofoils at these different values for v.

By our previously determined equation we find the values for part R_2 of residual resistance at these speeds; whilst part R_1 of residual resistance is constant and already obtained. So now we

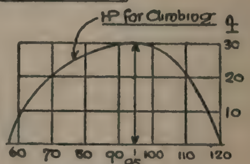
can plot out our curve of total resistance, or $R_1 + R_2, + R_D$.

If from these curves of propeller thrust and of total resistance now obtained we see that the resistance be less than, or equal to, the thrust at the maximum speed we are asked to accomplish, then this speed is, presumably, attainable.

TABLE FOR RESISTANCES.

$i°$	v (fps)	R_1 (lbs)	R_2 (lbs) $= .00503v^2$	L/D Model	L/D Full	R_D (lbs) $= 1900 \times D/L$	R_T (lbs) $= R_1+R_2+R_D$
1	120	68	72	10·0	11·7	162	302
4	89	"	40	16·2	21·6	88	196
7	74	"	28	12·4	13·9	137	233
10	65	"	21·	9·6	10·4	182	271
13	60	"	18	7·7	8·2	232	318
16	58	"	17	6·0	6·4	297	382

FIG. 17



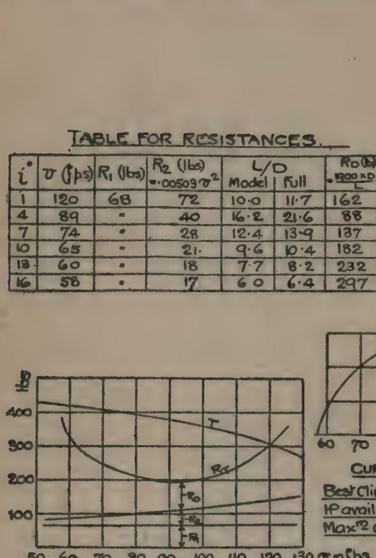
CURVE OF HP FOR CLIMBING

Best Climbing Speed = 95 fps

HP available at this Speed = 30

Max^m Climbing Rate

$= \frac{30 \times 550}{1900} = 8.7$ ft/sec



CURVES OF THRUST T, & OF HEAD RESISTANCES R_1, R_2, R_D & R_T.

CLIMBING SPEED

It remains to find the greatest possible climbing speed and see if the final requirement can be fulfilled.

The vertical height of the thrust curve above the total resistance curve at any point along the base gives us the surplus thrust at the corresponding base line value for speed.

This surplus thrust multiplied by value for speed gives us a value for foot lbs. per sec. available for climbing.

This value we may plot as a final curve of power available for climbing.

We then take the maximum Value (given us by the highest point on our curve), noting the speed at which this optimum value is attained.

Then our optimum value of power for climbing ÷ the total weight of machine gives us best climbing rate in feet per sec.

If this be decently over the requirement we can consider the preliminary design as finished.

IN CONCLUSION

In the first over-all design, methods for arriving at which I have attempted to outline, no pains should be spared to get the best and most compact disposition of external parts, and the best sizes and forms for them. In the structural design, which I have not touched upon, every detail should be considered most carefully to ensure that each is as simple and compact, and, therefore, as light for its strength as possible, and that for each is chosen the best material.

If this be done, using with due common sense every source of reliable data, and doing everything methodically and thoroughly, it is highly probable that the results will be good, and if one goes on working thus in subsequent designs, altering up empirical constants as found necessary or advisable from increasing experience, one will design better machines, and will know why they are improved.

It is because this system of methodical improvement is, I think, the basis of all true engineering advance, and because little thrashing out of tables and formulæ has been done so far (or at any rate published) from the data presently available, that I have tried in this paper to outline some methods for doing so.

I am painfully aware that much necessary matter has perforce been left out, and that much of what I have said is incorrect, but if it prove of interest or instructive, if it help in any way the betterment of this branch of engineering science, I am amply repaid for what time and effort it has cost me,

PART II

A SIMPLE EXPLANATION OF INHERENT STABILITY

By W. H. Sayers

THE question of inherent stability is one that has attracted much interest and caused much strife amongst all classes of those interested in aviation. It has been the cause of much activity on the part of transcendental mathematicians—to such effect that not only have they in many cases bewildered their readers but they are sometimes under suspicion of having successfully bewildered themselves. It is unfortunately also the case that many writers and students dealing with this question in simpler language than that of the mathematician have been led astray by the too apparently obvious.

The mathematical treatment of such a subject is of great value, but those capable of understanding the complex mathematics of others should be able to produce the required results themselves, provided they have a clear vision of the actual principles involved. Hence a simple straightforward explanation of the actual known principles by which inherent stability may be attained, should be of value to both the mathematical and the non-mathematical reader.

It may here be as well to warn the reader that in all probability the inventors of various inherent stability machines coming into the classes which will be dealt with later, will deny that they owe their stability to the simple causes herein explained, preferring to ascribe their results to much more complicated phenomena. It is frankly admitted that the action of certain stabilising devices is much complicated by many curious and incompletely understood causes, but the simple explanations herein given account in the main for the general effects produced—both qualitatively and quantitatively—which corresponds with the eating of the pudding.

Fig. 1.

Before proceeding further it may be as well to arrive at a clear understanding of what stability really is. We may take as an example the well-known little toy, shown in Fig. 1, consisting of a hemisphere of lead surmounted by a paper cone. Placed in any position it returns, immediately it is free, to the upright. As a matter of fact, it goes past the vertical position and oscillates slightly before coming to rest. This quality is stability and the stability is complete. It is to be noticed that this toy, in spite of its stability, requires only a very small disturbing force to move it far from its original position, but it returns very quickly.

Consider Fig. 2. This shows a balance arm having on it two equal sliding weights. These weights, being at A equi-distant from the centre, and having their centre of gravity below the point of support of the balance, the system is in stable equilibrium and betrays the same general characteristics as Fig. 1.

But move the weights out to the positions B. The system still remains stable, but it will be found that a much larger force must be applied to the arm to produce a similar disturbance—obviously since to move the arm through the same angle the weights have to be moved through a much greater distance. Not only this. After the removal of the disturbing force the return to normal position will be much more sluggish, and for small disturbances the system will be steadier, though not more stable. This is a point of considerable importance. An aeroplane having its heavy parts distributed over a considerable space will, in the

same way, be slower to answer to air disturbances, and will require more to stop her movements when once started, but, owing partly to the relative slowness of her movements, and partly to that slowness giving the pilot opportunity to use his controls, will appear steadier than a machine, otherwise similar, having all its large weights closely concentrated, and will generally be credited—usually unfairly—with greater stability than the livelier machine.

Now the aeroplane depends entirely on the maintenance of its correct flight speed for support, and, therefore, inherent stability implies that the machine possessing it shall always tend to increase its speed, if the speed is accidentally reduced. This quality can only be secured by the action of gravity, and acceleration in the line of flight due to gravity can only be obtained at the expense of a downward acceleration.

Now it is obvious that this accompanying downward acceleration, or rather the motion due to it, should be as small as possible, as involuntary downward motion is dangerous if the machine is low. Also, as the ratio between the downward acceleration and the corresponding horizontal one is the angle of descent with the motor stopped, or the gliding angle as it is usually called, it is a matter of importance, even when the machine is high, as effecting the choice of landing positions. Hence the importance of securing, as far as possible, that stabilising arrangements do not interfere with the efficiency of the machine.

Theoretically, any machine which possesses

the fundamental property of diving when it has lost its normal support from any cause is inherently stable, provided it is properly balanced fore and aft, for suppose such a machine to turn over till its wings are vertical. It will proceed to dive till it attains a vertical speed equal to its flying speed and will then flatten out and proceed on a course at right angles to the original. Which is to say that longitudinal stability alone will eventually bring a machine back from even a lateral disturbance but it will require a considerable amount of room in which to do so, as some, at any rate, of the forward velocity possessed by the machine at the moment of disturbance is wasted, owing to the change of course necessary, which in itself is a further objectionable feature.

Practically, therefore, it is desirable to correct lateral disturbances independently of longitudinal ones, and in addition it is well to reduce disturbances of all kinds as much as possible, partly on the score of comfort, but mainly to reduce the space necessary for recovery.

A very large number, in fact the majority, of existing machines probably possess actual inherent stability in the sense that, placed at a sufficient height in any position, they will, if all the controls are locked in normal flying position, or in many cases left entirely free, eventually assume their normal position. In most cases, however, a very great height would be necessary for this recovery.

Hence, practically, other qualities than the fundamental longitudinal stability are necessary,

and it is convenient to consider the question in three divisions :

I.—Longitudinal stability.
II.—Lateral stability.
III.—Directional stability.

Fig 2

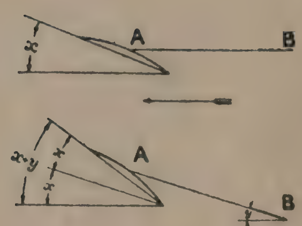


Fig 3

LONGITUDINAL STABILITY

This branch of the subject is probably more generally understood than any other, the principle of the longitudinal V, as it has been termed, having been employed by experimental workers in quite the dark ages. Fig. 3 shows the most common form in which this principle—that of setting the leading surface at a greater angle of incidence than those following it—is employed in practice. A is the actual lifting surface of the aeroplane, which at its normal angle of incidence X, supports the whole machine, the centre of pressure of A coinciding with the centre of gravity of the aeroplane. B is the stabilising surface or tail, so set as to produce no lift at the normal angle. Now, suppose the machine to pitch nose upwards through the angle Y. The total lift on A will not increase greatly, as the extra resistance due to the increased angle will slow the machine down. (Note we are assuming at the moment that the machine has just sufficient power for horizontal flight.) The centre of pressure of A will move forward, which will tend still further to increase the pitching, but the tail surface B, instead of having no angle of attack and no lift, has an angle Y and a consequent lift, tending to swing the tail upwards. and restore the normal position.

Or, to look at the matter in another way, suppose a machine, having two surfaces in tandem with the weights so distributed that one surface is much more heavily loaded than the other, to be in still air and with no forward velocity. Obviously it will

Fig 4

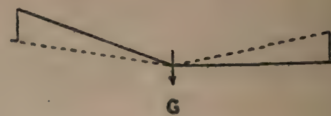


Fig. 5

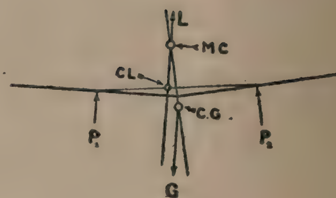


Fig. 6

drop, and equally obviously the more heavily loaded surface will drop faster. If this more heavily loaded surface is the front one, the machine takes up a diving position and picks up speed, and consequently begins to lift. Any arrangement of planes in which the leading plane, or even the leading part of a plane, has a greater angle of incidence than that which follows, shows this tendency,—i.e., a plane with a double camber—the leading part cambered normally and the trailing part cambered in the reverse way, may be in

itself stable, and Fig. 4 shows, by the little shaded sections, how a swept-back wing with a negative tip provides in itself the longitudinal V. This method of securing longitudinal stability is in practically universal use, and actually produces the desired result.

It is obvious that if a machine in flight meets an end-on gust its air speed is momentarily increased and that it will rise till its speed is reduced, and conversely as the gust dies away that the air speed falls and that the machine must dive to recover speed. These disturbances are essential to the stability, but their actual magnitude may be diminished by improvement of the gliding angle.

But an end-on gust may produce other disturbances. If the centre of head resistance is above the centre of gravity of the machine, during the growth of the gust there will be a tendency to throw up the nose, and during its dying away to dip the nose, tending to exaggerate the movements which are due to the stabilising force. If, on the contrary, the centre of head resistance is below the centre of gravity, the forces will have the opposite tendencies, and will oppose the stabilising forces. The latter condition is obviously dangerous and the first is at least objectionable. Therefore it is necessary that the centre of total head resistance of the machine should be as nearly as possible in the same horizontal line as the centre of gravity, in order that the greatest stabilising effect should be combined with the least disturbance.

LATERAL STABILITY

Pure inherent lateral stability, i.e., that form of stability which ensures that, while the flight speed of the machine is sustained, it shall always return to an even keel on the removal of the disturbing force, is quite simply attainable.

In Fig. 5 the dotted lines show a pair of planes with a dihedral in a normal position, the full lines show the same planes tilted laterally. As the two vertical lines show, in the tilted position there is a greater resistance to downward motion on the low side than on the high, hence the high side will drop relatively to the low, till the normal position is regained. Provided that the centre of gravity is not too high, there will always be a restoring force with this arrangement.

Fig. 6 may be of some interest in this connection. Here P_1 and P_2 are the resultant pressures on each half of the wings at right angles to the planes. When the wings are tilted downwards to the left, say, the vertical effect of P_1 and P_2 will be slightly displaced towards the left, as shown at L, acting through CL (the centre of lift), and the vertical line through CL will intersect a central plane—about which the machine is symmetrical and on which the centre of gravity must lie—at some point above the centre of lift, as MC. As long as MC is above the centre of gravity the machine is stable laterally and MC is equivalent to the " metacentre " of a ship, the vertical distance between MC and CG being the equivalent of metacentric height. The conditions to be satisfied to provide

simple lateral stability are practically the same in the two cases, and in the aeroplane the provision of a sufficiently low CG satisfies them, even without the dihedral. Unfortunately, owing to the large value of the disturbing forces (gust effects, etc.), compared with the supporting forces, which are also the righting forces, and to the fact that a large disturbance will greatly diminish these supporting and righting forces, we have to consider methods of reducing disturbances in order that recovery may become quick and may be completed before striking the earth.

Now a machine is disturbed laterally because one side gains lift, or the other loses it, the side having the excess of lift rising, that having the deficit falling. In a wing of rectangular plan form —that is with uniform chord—if the pressure per square foot is uniform it is fairly obvious that the total pressure acts as though it were a single force at the centre of the wing, i.e., the centre of pressure of each wing is half-way along the span.

Fig. 7 shows a wing of triangular plan form, tapering to a point. If such a wing is acted on by a uniform pressure per square foot it will be seen that the total pressure on any strip, say, 1 ft. wide, will be proportional to the fore and aft length of that strip, and that the pressure on longitudinal strips will be proportional to the length of the arrow under that strip (in the lower part of Fig. 7). Hence the total resultant force will be as the large arrow (R) acting closer to the body than halfway. Also if one wing receives an excess pressure which is uniform per square foot the resultant of that

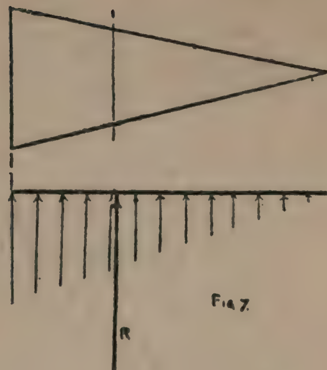


Fig. 7.

excess will act as closer to the body, and from the well-known principle of the lever, will produce a smaller effect on the machine.

Now, obviously, any less degree of taper will produce a similar, though less, effect, and so also will reduction in the camber and angle of incidence ("wash out") from the body to the tip, for any pressure due to air moving past the wings with a velocity in the line of flight. That is, a "wash out" would not make any difference to the effect of purely vertical gusts, if such things could exist.

Now, consider a wing, tapered or washed out so as to bring the Centre of Pressure close to the

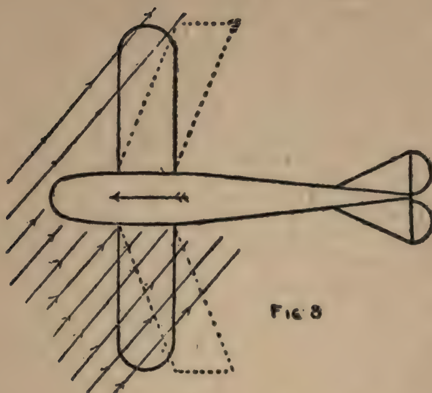


FIG 8

body side, but provided with an extension set at a negative angle. This extension produces a downward pressure, which diminishes the total pressure on the wings, but also moves the point of application, or centre of, total pressure closer still to the body, and since this negative pressure is acting much further out (at a larger radius) the centre of total pressure may be caused to pass beyond the base of the plane without completely neutralising the lift.

If we can thus cause the centre of total pressure of such a wing to lie on the centre line of the machine (and this is possible in theory at any

rate), then one wing will maintain the machine in balance laterally, the other side being absent. If this condition is attained, then as long as each separate wing is in uniform air, however different may be the conditions around each wing, no force tending to overturn the machine sideways exists.

This condition does not occur, of course. But Fig. 8 shows an aeroplane in a side gust. Since the machine has a forward movement, the actual movement of the air during the gust must be diagonal, and, as the diagram shows, one wing is practically unshielded, i.e., if the gust is uniform that wing is subject to uniform conditions, and on this wing the whole compensating effects of negative tips would take effect, leading to at least a considerable reduction in the disturbance. The far wing is partly and unequally shielded, the tips receiving the least shelter. The dotted lines show that sweeping back the tips places the far side wing in more nearly uniform shelter. The figure is, of course, diagrammatic only, and should not be taken as representing that a large portion of the far wing is completely shielded—were this the case the problem would be, indeed, hopeless. In fact, with swept-back wings and properly proportioned negative tips the uncorrected disturbances due to uneven shielding are quite small.

VERTICAL FINS

If the wings form a dihedral angle, then in addition to the extra lift caused by a side gust on the near or unshielded wing, there is a tendency to lift the near side and depress the far side, due to the fact that at right angles to the line of flight the near wing has a positive, and the far a negative, angle of incidence.

This may be compensated for by enlarging the negative tip surface, or by providing a vertical fin below the centre of gravity, which will produce an opposite tendency when struck by the gust. This fin may be made sufficiently large to overcome the extra lift on the unshielded wing in addition, when the negative wing tips may be dispensed with—as was proposed in the Ding-Sayers monoplane.

It may be noted that vertical fins above the centre of gravity have frequently been proposed, the theory being that, on a machine tilting sideways there would be a tendency to slide towards the low side, and that the consequent air pressure on the fin would push the machine straight. It is obvious that this fin would be acted on by side gusts and tend to increase the disturbance due to them. It is, in fact, equivalent in most ways to a simple dihedral angle, but inferior in the degree of stability obtainable.

DIRECTIONAL STABILITY

It is obviously desirable that an aeroplane shall not be liable to be deflected from its course by any disturbance. Now a purely end-on gust, if uniform, will not have any tendency to throw the machine off its course, no matter what its force. In the case of a side gust the unshielded wing will have an increased resistance as compared with the shielded wing. But more important than this is the effect of such a gust on the body, or any other side surface, such as fins or side faces of a wing at a dihedral angle.

To secure that no turning tendency shall be produced it is necessary that the lines of action of the total resultant side pressure shall act through the centre of gravity of the machine. Then the only effect on the machine will be bodily motion sideways without any turning effect. Unfortunately, the centre of side pressure varies in position with changes in the direction and the strength of the gust; so complete balance under all conditions is impossible.

Now if the centre of side pressure is forward of the CG, the nose of the machine will turn with the gust, and the machine will turn down wind, which will momentarily reduce its air speed. If, on the contrary, it is behind the CG, the tendency is to turn up wind and increase the air speed. The first case is dangerous—the latter safe, therefore it is desirable to keep to such an arrangement of vertical surfaces as will always keep the centre of side pressure aft of the CG.

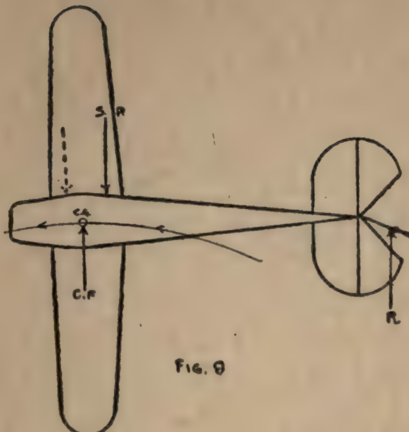


Fig. 9

But the most important aspect of this question arises when the machine is turning under the action of the rudder. Fig. 9 shows this case. The rudder of the machine is turned to the left, and a pressure (R) acts on the rudder, tending to swing the tail of the machine to the right. Momentarily the machine moves through the air crabwise, which produces a side pressure (SP) on the right-hand side. Under these two pressures the machine commences to turn in the curved path shown. As soon as the machine starts actual turning, a third force—centrifugal force (CF) commences to act through the CG of the machine, and towards the outside of the curve.

Now, if the side pressure SP acts behind the centrifugal force—i.e., behind the CG—it will be seen that centrifugal force opposes the turning, and when the rate of turning has reached a certain value the three forces are in balance and the machine will continue turning steadily. If the rudder is now put back into neutral, R disappears and CF and SP tend to take the machine off the turn, and both of them disappear as soon as the machine has stopped turning.

But suppose SP to act in front of the CG, as at the dotted arrow. Then CF and SP themselves provide a tendency to turn to the left, added to the tendency due to the rudder, and instead of reaching a steady state of turning the machine will turn faster and faster. Even when the rudder is put back to neutral, SP and CF still keep increasing the rate of turning. As a matter of fact, as the rate of turning increases SP tends to move further forward, and to increase, hence a machine may start to turn with SP behind the CG, and as the rate of turning increases, SP may move forward till it is in front of the CG, and may eventually become so large and so far forward that even with the rudder hard over in the opposite direction the turning continues.

This is the explanation of the spiral nose dive effect. The theory of the elevator acting as rudder when the machine has a large bank does not explain the phenomenon, as unless there are at least two forces acting independently of the pressure on the control surfaces the machine will cease to turn when all controls are placed in the neutral

position. The late Lieut. Parke's experience at Salisbury in 1912 proved that this is not the case.

Now it is obvious that if a machine slips sideways—say, is stalled, rolls over to one side and slides downwards—that a side pressure similar to SP will be produced. Also the inertia of the machine will produce the equivalent of CF, or rather will produce CF, as centrifugal force is only an inertia effect, and the turning effect due to these forces appears. Hence the spiral may occur without any use of the rudder at all. If the direction of a machine is changed, extra power has to be supplied, to give it air speed in its new path, and if the turn is so rapid that the engine margin of power is not sufficient for this purpose —this extra work must be done by gravity—the machine must dive, and the faster the turn the steeper the dive, until when the turning rate is such that a force equal to the whole weight of the machine is required to provide the air speed the machine will descend vertically. Therefore this increasing turning effect produces that most deadly of all aeroplane accidents—the spiral nose dive.

The side pressure here evidently includes that due to all possible causes as pressures on the body, on any vertical fins, or on upturned sides of wings. There will obviously be a side pressure on wings with a dihedral when turning, or on flat wings when banked, and this side pressure may be very large, and is bound to act not far from the centre of gravity, owing to the position of the wings. Hence, as far as possible, this side pressure must be kept small. Obviously, the wings themselves

cannot be reduced, but swept-back wings with negative tips must always have their centre of side pressure farther back relatively to their centre of lift than normal wings. Also the negative tips tend to reduce banking on turns to within reasonable limits, reducing thereby the side area due to wings on which such pressure acts.

Fins beneath the centre of gravity, when acted on by the side pressure, oppose banking with the same desirable effect, and may obviously be so arranged as to have their own centre of side pressure as far aft as may be desired, thus securing this essential form of stability.

With fins above the CG the tendency, on the contrary is to increase banking on turns, or to increase the tilt due to a side gust, and therefore to increase the total value of side pressure possible, and particularly the most dangerous component —that on tilted wings—and are hence objectionable and even dangerous, as tending to produce the very catastrophe for which they have been proposed as a remedy, unless made extremely large and placed very far back.

At the time at which the preceding statements on spiral instability were written nothing had been published on this subject (so far as is known to the writer), with the exception of certain paragraphs in "Aerodonetics" (Lanchester, "Aerial Flight," Vol. 2); but in the meantime, Mr. Bairstow has dealt with the matter in his lecture before the Aeronautical Society (January 21st, "The Stability of Aeroplanes"). Both Mr. Lanchester and Mr. Bairstow claim that the cure for directional

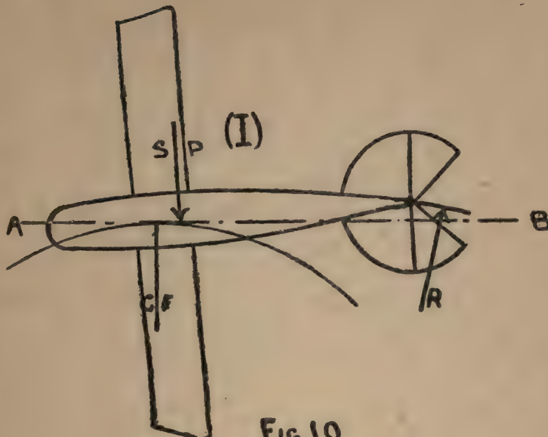
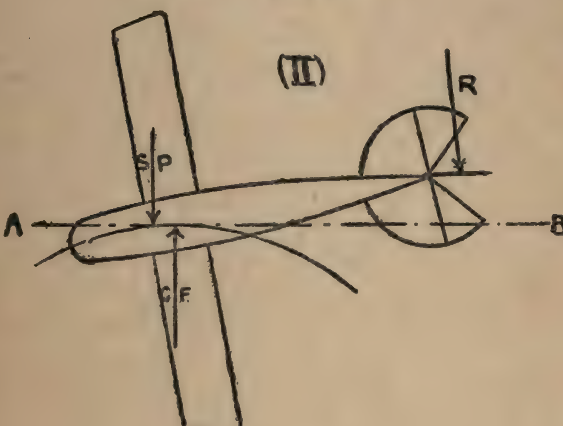


FIG 10



instability lies in a forward centre of side pressure, and apparently prove their assertions by experiments with models, thus definitely contradicting the writer's conclusions. It may be as well, therefore, to go into this question a little more completely.

In Fig. 10, I is a replica of Fig. 9, except that it shows how the centre line of the machine deviates from the tangent to its circular path, which is the momentary line of flight—i.e., that it "crabs" slightly, thereby producing the side pressure, SP. II shows the case of the machine with the forward centre of side pressure. In this case, as soon as the rudder is put slightly over, "crabbing" commences, and the forward side pressure swings the machine still further askew until the angle between AB (the momentary line of flight) and the centre line of the machine is greater than that between the centre line of the machine and of the rudder. The force on the rudder then becomes reversed and acts from the outside, so that we again have SP and R acting in opposition, though their respective rôles are reversed. The machine, as long as the rudder is held in such a position, will turn steadily at a definite radius, with the rudder checking the tendency to spin.

Now in a model aeroplane the rudder is actually a fixed surface, hence this arrangement apparently gives the required stability. But in any actual aeroplane it is not fixed, and may be put into a position of no resistance to turning and will take that position itself if a rudder wire breaks or the pilot's foot slips from the bar, when the machine becomes completely unstable and spirals violently.

AN IMPORTANT OVERSIGHT

A rudder is not a fixed surface and must not be counted on as such in a full-sized machine—although it usually is, and acts as such, in a model.

It may be remembered that Mr. Bairstow referred to marked lateral oscillations in his " stable" models. What happens in this case is that the model, on tilting sideways, slides down slightly and produces the side pressure SP, which tends to spiral it to the other side. This tendency is checked by the damping of the very large fins and by the reversed rudder action—but with a free rudder this model would spiral and nose-dive towards the (original) high side after each lateral disturbance ; while the machine with the side area aft merely dives and swings towards the low side without any tendency to spiral continuously.

Mr. Bairstow's " unstable " model—produced by removing the front fin—was in the condition already referred to in which the centre of side pressure is at the commencement of a turn behind the CG, but moves forward as the turn progresses. This change over is extremely dangerous—much more so than the really unstable condition, with the permanently forward centre of side pressure, as this latter, on account of the permanent negative pressure on the rudder-bar, gives the pilot a continual warning that the machine is trying to spin, while the change over is sudden and disconcerting.

A WARNING AGAINST ASSUMPTIONS

From the foregoing it would appear as if in order to secure complete immunity from directional instability, it is only necessary to supply an ample rear fin, and that it is desirable to reduce the dihedral style to as small a value as is consonant with the requirements of pure lateral stability so as to avoid undue banking.

Unfortunately the case is somewhat more complex. In order to be able to turn without excessive "crabbing," or skidding sideways, it is necessary that the side pressure at a small rate of movement sideways shall balance the rudder force and centrifugal force.

Now if the centre of side pressure is very close to the centre of gravity, and the side pressure is nearly equal to the centrifugal force in magnitude, there will only be required a quite small rudder force to provide the required state of balance. But if the centre of side pressure be very far aft of the centre of gravity the rudder force required to produce a state of balance will be greatly increased. That is to say that the pilot will have to make greater muscular efforts to steer the machine and the machine will also respond less rapidly and easily to the rudder.

Also, since centrifugal force increases as the radius of turning decreases it is necessary that on sharp turns both the side pressure and the rudder force should increase. The rudder force will increase with the increase of the angle to which the rudder is put over, but to increase the side pressure

either the rate of motion sideways, or the side area, must increase. As it is desirable to keep the sideways motion as small as possible it is necessary to increase the actual side area, and that can only be done by increased banking, thus making the inclined faces of the wings effective for this purpose.

For these two reasons a machine which shall be easily steered can only be made by approaching very closely to the condition in which the centre of side pressure corresponds with the centre of gravity and the margin between this condition and one of instability is very narrow.

EXPERIMENTS NEEDED

In this connection it may be remarked that a series of experiments are desirable on the behaviour of bodies of the form used as aeroplane fuselages or nacelles, and of flat surfaces moving in a curved path and at a slight angle to that path.

Very little is known on this subject, but there is much evidence showing that differences in body form may completely alter the behaviour of a machine in this respect, and one might hazard a guess that in Fig. 11 the centre of side pressure of A would occupy a considerably more forward position than that of B when acted on by a wind as indicated by the arrows, and that a machine with a fuselage or nacelle entry such as A might be unstable, whereas an otherwise identical machine with a body entry such as B might be stable.

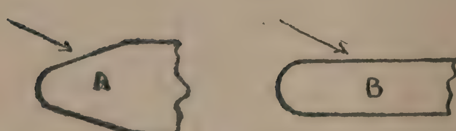


Fig. 11

STABILITY IN VARIOUS TYPES

Having now, if not briefly, at least rather hastily, considered the question of inherent stability in all its more important aspects, we will consider one or two types of machine in order to notice to what extent the various desirable features may be combined, and what disadvantages from other points of view such combinations may have.

1. Machines with planes at right angles to the line of flight, with tapered and or "washed out" planes. Appreciable reduction in the disturbance due to side gusts. Combined with the longitudinal V, and a proper vertical position of the CG, both longitudinal or lateral stability may be obtained, with a fair degree of steadiness. With a correct disposition of side surfaces ensuring that the centre of side pressure is always aft of the centre of gravity, immunity from the uncontrollable spiral nose dive is secured.

2. Machines as above with negative wing tips. Partial or complete neutralisation of disturbing forces due to side gusts, reduction of tendency to overbanking on turns, leading to further reduction of risk of spiral nose dives. In combination with the longitudinal V, correct position of CG, etc., has the same good qualities as No. 1, with an enhanced degree of lateral steadiness and immunity from spiral dives.

In both the above forms the tendency is rather to increase the sensitiveness of the machine to the warp while longitudinal controls are normal.

3. Machines having negative tips and swept-back

wings. These give the same lateral steadiness as the above, a greater and possibly a complete immunity from side slip, owing to the centre of side pressures on such wings being aft of the centre of normal pressure, and have in the plane themselves a longitudinal V which can be made to provide longitudinal stability. As with previous classes, lateral controls are, if anything, unusually sensitive.

If, like the Dunne, the planes are relied on for longitudinal stability, and tail planes and booms are not used, they may be more sensitive to elevator control than normal machines, owing to the better concentration of weights.

As with the other forms, the stability due to the wings themselves may be supplemented by any of the other methods of stabilising already considered. In practice, machines of this type show themselves to be safe, steady and sensitive to control. It must be noted that all machines with negative tips must lose in efficiency somewhere, as the head resistance of the part of the wing beyond the non-lifting line not only is accompanied by no lift, but by an actual negative lift. Actually owing to several causes—one being the large value of dead resistance, i.e., body, chassis, etc.—this loss in efficiency is not prohibitive, some machines with negative tips having better gliding angles than some not so provided.

4. Machines in which a dihedral angle and a low centre of gravity are relied on for lateral stability. In this case disturbance due to lateral gusts is great; also, when turning a corner, there

is a tendency to overbank, owing to centrifugal force acting below the centre of side pressure, hence risk of side slip. By the adoption of vertical fins below the centre of gravity both these disadvantages are overcome. By suitable proportioning of the fin, i.e., by keeping its centre of side pressure back far, immunity from spiral diving can be obtained. This arrangement can, of course, be combined with the longitudinal V, giving, as far as can be predicted, as good results as any combination yet tried. In this case no interference with the elevator controls occurs. With the fins some damping of the warp and rudder controls is inevitable—owing to the large fins necessary. This damping, however, could not be greater than about one-tenth of the damping due to other essential parts of the machine, which in practice would be inappreciable. No example of this type has been completed, but the behaviour of certain deep-bodied monoplanes, notably the R.E.P. and Clement-Bayard, tend to confirm the value of this method.

There are doubtless other forms of machine claiming inherent stability, but little or nothing is known as to their performance or of the ideas which have prompted their designers.

It will be noted that the question of the controllability of the various types of stable machines has been referred to, and that very little disadvantage as compared with normal machines has been admitted. It is assumed that the machine has been arranged to be stable with all controls in the normal condition, and it can be easily seen that if

sufficiently powerful controls are fitted the inherent stability may be largely or completely destroyed.

For instance, if a sufficiently powerful rudder is held hard over, any machine must spiral and nose dive. But, except in the case of a jammed control, this does not matter, as the pilot can at once stop the effect, by leaving the rudder free, provided the machine has the proper disposition of side surfaces. Therefore the pilot can use his controls to any extent in an emergency, at the expense, of course, of a dive, with the certainty that after the removal of the control force the machine will return to the normal conditions. This is not true of an unstable machine—as shown in the section on spiral dives. A large amount of the prejudice on this head arises from the confusion—already pointed out—between the slow movements of the machine whose weights are widely distributed, and the lively motion of the one in which they are concentrated. The first are usually credited with a large amount of stability by those who see them in flight. They are inevitably slow in answering their controls, hence the myth that a stable machine does not answer well to controls. Actually this quality from which the steadiness arises is adverse to stability and the objection is groundless.